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FACULTY OF HUMANITIES

Department of Archaeology

Volume I of I

Virtualizing Conservation:
Exploring and Developing Novel Digital Visualizations for Preventive and Remedial Conservation of Artefacts

by

Eleni Kotoula

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF HUMANITIES

Archaeology

Thesis for the degree of Doctor of Philosophy

VIRTUALIZING CONSERVATION: EXPLORING AND DEVELOPING NOVEL DIGITAL VISUALIZATIONS FOR PREVENTIVE AND REMEDIAL CONSERVATION OF ARTEFACTS

Eleni Kotoula

Critical evaluation of the actions involved in conservation practice reveals that the limitations of traditional approaches for examination and treatment influence decision-making and affect the artefacts' interpretation and display. Such problems demonstrate the technological needs and underlie the research aims for the development of scientific conservation and practice. This research evaluates the application of digital technology in conservation of antiquities and works of art by proposing alternative digital methodologies for examination, restoration and conservation documentation. Its value is demonstrated by case studies, covering a broad range of artefacts types and a variety of materials. The key elements of the proposed methodology are the following:

· Development and application of computational imaging, computer vision and digitization techniques for enhanced examination and visual analysis

· Graphical 3d modelling and physical 3d reproduction for interventive treatment

· Workflows for digital and conventional conservation documentation

This thesis addresses to what extent 3D technologies contribute to conservation objectives, defined as the balance of preservation, investigation and display, considering also the ethical and theoretical aspects.

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List of accompanying materials

A USB stick containing the Digital Library (see Appendix D for structure of the digital library, contents, file formats and naming convention) is submitted as accompanying material.

DECLARATION OF AUTHORSHIP

I, Eleni Kotoula, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Virtualizing Conservation: Exploring and Developing Novel Digital Visualizations for Preventive and Remedial Conservation of Artefacts

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

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Date: 1 September 2015

Glossary

Algorithmic rendering is a mathematical method that can apply selected mathematical “filters” to a sequence of digital photographs of a cultural or natural history subject. The result is a new digital image of the subject disclosing its features in a new and useful way.

Augmented reality (AR) refers to a system in which the user views and acts within an enhanced version of the real world. The enhancements are virtual (computer-generated), and can include objects or information.

Automatic identification and data capture (AIDC) is a group of methods for automatic identification of objects, collecting data about them, and entering that data directly into computer systems, such as Radio Frequency Identification (RFID) and bar codes.

Bidirectional reflectance distribution function (BRDF) describes how a material interacts with light, defines a material’s property to distribute light, characterises the colour of a surface as a function of incident light according to the direction of a viewing.

Bump mapping stimulates the surface irregularities without the need for geometric modification.

Computer vision is the science of endowing computers or other machines with vision, or the ability to see.

Diffuse colour mapping is a common materials modelling technique. The map assigns a pattern or texture to a material's diffuse colour. The colours of the map replace the material's diffuse colour component.

Haptics is a vibration or other tactile sensation received from a computer or electronic device.

Hemispherical Harmonics (HSH) is a model of distribution across a hemisphere of directions.

MAXScript is the built-in scripting language for Autodesk® 3ds Max® and Autodesk® 3ds Max® Design.

Mesh is a collection of vertices, edges and faces that defines the shape of an object.

Mixed reality (MR) refers to a system that combines real and virtual objects and information (Bowman, 2008).

Normal is a unit vector that is perpendicular to the plane tangent to the surface at the given point. It is usually taken to be pointing outward away from the surface.

Normal map consist of red, green, and blue values translates to x, y, and z coordinates, allowing a 2D image to represent depth and fake lighting details based on the colour associated with the 3D coordinate.

Point cloud is a cloud of points, a set of data points in 3d space intended to represent the external surface of an object.

Rendering is the conversion of a high-level object-based description into a graphical image for display.

Soft-box is commonly used photographic equipment which provides a diffused soft light.

Specular enhancement is one of the rendering modes available in software used to access rti and ptm files. The specular enhancement algorithm separates the shape-based reflections and the diffuse RGB colour.

Specular imaging is a set-up used for photographic documentation of artefacts. According to the position of the light source and the camera in relation to the object, either parallel or opposite, the specular properties of the object can be documented.

Texture mapping is the technique used to enhance a 3d model by warping a 2D texture map onto its surface.

Trans-illumination RTI is a computational visualization of an object derived from a dataset of transmitted images captured in the visible spectral area. The camera records the visible light transmitted through the object.

Trans-irradiation RTI computational visualization of an object derived from a dataset of transmitted images captured in the near infrared spectral area. The camera records the radiation transmitted through the object.

Virtual reconstruction/restoration is defined as the reconstruction/ restoration of something not physically existing but made by software to appear to do so.

Virtualization is defined as the conversion to a computer-generated simulation of reality, a virtual version of something.

Visualization is defined as the process of making something visible to the eye. The process of creating digital surrogates that can be viewed in order to represent the appearance of things.

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Part 1: Current digitization and imaging approaches

Chapter 1: Introduction

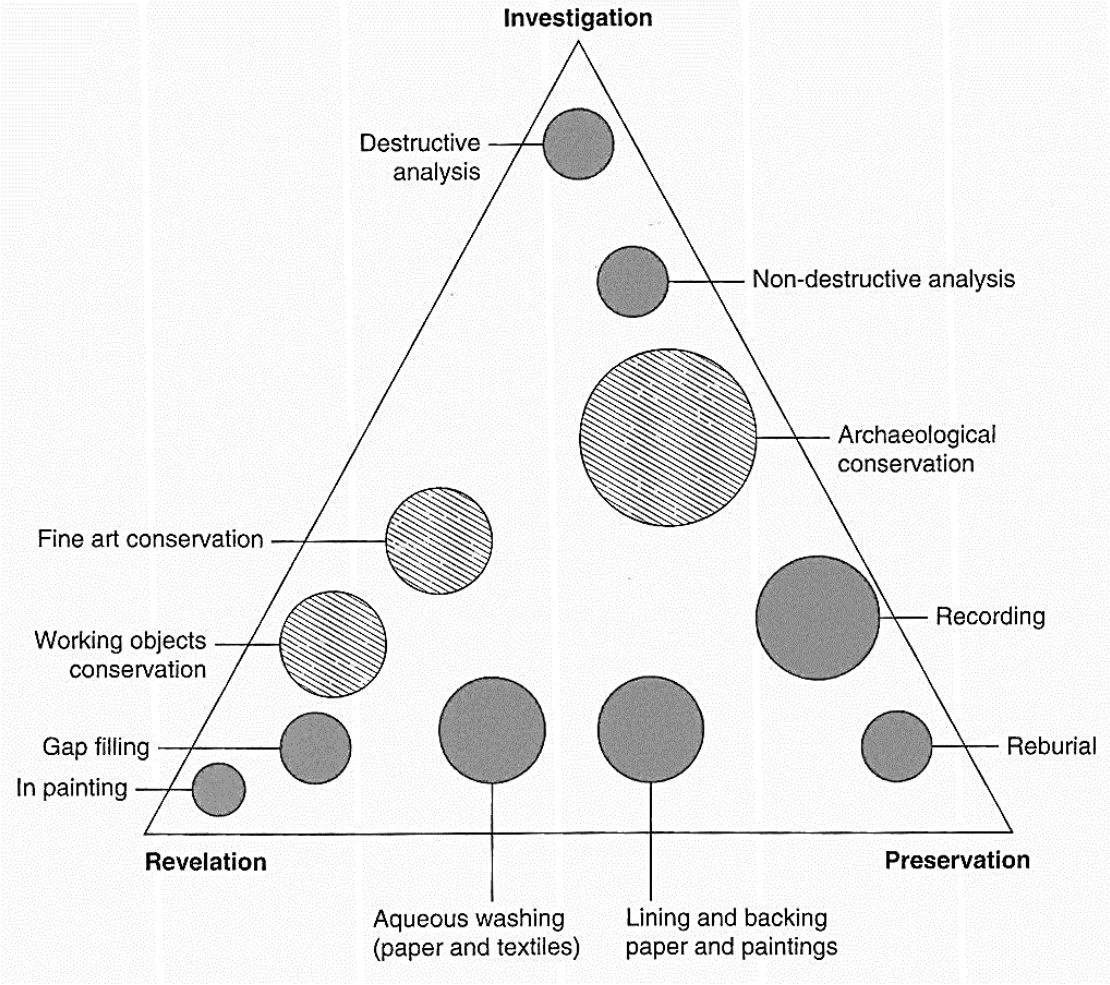
1.1 Conservation of antiquities and works of art

The conservation of antiquities and works of art is caught between the double function of artefacts; as both resources for archaeological and historical information and as displayable objects; as it attempts to control the processes of decay, minimise deterioration, and prevent alterations and damage. The cornerstone of conservation is the requirement for long term preservation, balanced with the needs to investigate and interpret, access, use, display and reveal objects and their attributed values. These ideas were reflected on the RIP (Revelation-Investigation-Preservation) balance diagram[1] (Graph 1), a triadic graph which presents the aims of conservation (Caple, 2000) and the conservation conceptual model[2] (Watson, 2010) (Table 1) According to the first Article of the Professional Guidelines published by the European Confederation of Conservators-Restorers' Organizations (ECCO, 2002), the role of conservation is not restricted to the '*preservation of cultural heritage for the benefit of present and future generations'*, but also covers '*the perception, appreciation and understanding of cultural heritage in respect of its environmental context and its significance and physical properties*'. Hence, conservation treatment takes into consideration contradictory aspects of

[1] The triadic graph incorporates the three opposing goals; revelation, investigation and preservation and includes main conservation actions, such as recording, non-destructive and destructive analysis, gap filling, in painting and recording as well as the basic conservation sub disciplines, those of archaeological and fine art conservation. In each corner of the triangle an extreme conservation action is located; the destructive analysis for investigation, reburial for preservation and in painting for the revelation. Actions of less extreme character are located in the space between these extremes.

[2] The matrix presents the main conservation objectives; accessibility, durability, integrity and practicality related to four conservation actions, namely investigation, intervention, prevention and communication. In the intersection boxes the sub actions executed in the service of conservation objectives are presented.

artefacts, both the material and the conceptual, the tangible and the intangible, and not only the scientific but also the aesthetic (Pye, 2001).



Graph 1: The aims of conservation displayed using the RIP balance diagram (Caple, 2000, p.34).

Table 1: The elements of conservation: A conceptual model (Watson, 2010, p.12).

Objectives	Actions			
	Investigation	***Intervention***	***Prevention***	***Communication***
Accessibility Making the artifact in its historical form accessible and understandable to the present generation *(aesthetic / cultural integrity)*	Analyze internal evidence of missing or altered material for visually and functionally accurate reintegration. Where internal evidence is missing, analyze evidence from related examples and historical documents. Scientific analysis of historic materials and construction.	Restore historical form and aesthetic qualities. Reduce concretions that obscure object. Replace or infill missing material based on evidence.	Design safe and accessible exhibit and storage environments. Balance accessibility with use to limit wear and tear. Turn to complete or partial reproductions to reduce or eliminate wear of historic artifacts or most vulnerable components.	Advocate aesthetic re-integration (restoration). Share results of investigation; participate in interpretive dialog. Record interpretations revealed during treatment. Collaborate with owners and other shareholders.
Durability Helping the artifact survive unchanged for study and use in the present and future generations *(structural and chemical integrity)*	Analyze efficacy of conservation materials. Analyze properties of materials: physical, structure, stability, and aging. Analyze deterioration causes, effects, byproducts, and stabilization. Analyze conservation materials for stability and aging. Analyze destructive effects of environment and use.	Stabilize. Clean surfaces of destructive deposits. Re-attach loose components. Consolidate friable surfaces and unacceptably fragile materials. Isolate incompatible materials Add protective coatings or barriers.	Identify and reduce hazards to objects and to people working with them. Reduce destructive environmental conditions. Monitor environmental conditions. Design safe moving containers and procedures. Maintain emergency preparedness.	Advocate stabilization. Recommend maintenance and preservation procedures. Advocate preservation statutes.
Integrity Protecting for future generations the historical content physically encoded in the artifact; stewardship *(physical integrity)*	Analyze condition problems and minimally intrusive treatment alternatives. Analyze material evidence. Identify materials and their historical uses to differentiate historical construction, use, and alteration. Analyze construction methods for effect on condition, stability, and physical state. Investigate object's past context and history to corroborate and interpret physical evidence.	Minimize interventions. Use highly targeted methods. Consider non-treatment. Select treatments that are minimally intrusive. Make interventions detectable. Aspire to 'reversible' treatment alternatives. Consider preservation-worthiness of past alterations.	Safeguard original material and other cultural content. Monitor and document changes in condition. See to the archival storage of components and materials removed during treatment.	Advocate preservation of evidence and evolved state. Collaborate with shareholders to accommodate diverse values. Record condition assessments and conservation interventions. See to the archival storage of documentation. Recommend methods to protect vulnerable material evidence.
Practicality Adapting to economic, safety, and human resource considerations	Avoid investigations to answer irrelevant questions. Limit investigation to fit time and money constraints.	Reduce intervention to fit time and cost constraints. Increase intervention to enhance economic values. Concede to lab safety.	Balance cost and benefit in planning preventive conservation measures. Be practical in managing risk for artifacts.	Keep documentation appropriate but economical in time and cost. Advance the discipline through publications and other discourse.

Ward (1986) recalls the words of a speaker in the Hungarian Institute of Conservation and Methodology of Museums during the 1970s, which characterised conservation-restoration interventions as '*a race against time*'. In such a race every alteration, form of damage and evidence should be carefully examined, in order to lead to conclusions regarding characterization of the object and its condition. These features, which are formed during the artefacts' '*life*', are the basic components for the exploration of the biography of the artefact[3]. Moreover, the same features, in addition to the intangible aspects of the artefact, determine the goal of treatment and treatment type (conservation decision making). The changes introduced during treatment, after discovery, and throughout the artefact's museum life, including treatment history, not only in appearance (including geometry, colour and texture), but also in chemical structure, are among the most influential processes that determine the artefact's future, and dramatically affect its interpretation. Remedial treatment has a direct influence on chemical and physical properties of the objects, while preventive conservation or environmental preservation activities affect the object indirectly, as they can change its condition by altering its environment (see also Appendix A1). As a result, conservation can be understood as an open window to the artefact's past, and one of the most influential parameters for its future. There is no doubt that it is necessary to fully understand every conservation operation as an episode of unique significance during an artefact's lifetime (Appelbaum, 2007).

1.1.1 Applied conservation research

Applied conservation research aims to development alternative methods, able to efficiently deal with an artefact's conservation problems complexity. The new strategies under development have to be in accordance with conservation's ethical and theoretical background, taking under consideration the ideas of post-minimal intervention as an attitude (Villers, 2004) and re-treatability (Appelbaum, 2007), so as to secure the durability and protect the material and aesthetic integrity of the object, as well as its intellectual meaning. Moreover, the proposed methodologies have to respect conservation

[3] The idea of artefact biographies has been extensively discussed in literature (Schiffer and Miller, 1999; Gosden and Marshall, 1999; Jones, 2002)

objectives by providing enhanced accessibility to artefacts, whilst being practical, cost-effective and affordable. However, meeting conservation objectives, usually conflicting ones, is not a straightforward process, due to the sensitive balance between the ethical considerations and practicalities of conservation. The way the ethical and theoretical basis of conservation informs practice, while conservators are in search of the *ideal state*[4] of the artefact, results in conservation dilemmas, which have been a matter of scientific controversy and debate. For example, in case of objects with long biographies conservation decisions may lead to different ideals states, each one emphasizing the appearance of the object in different events.

Conservation theory has discussed the multi-level relation of science and technology with conservation. The development of physicochemical techniques (art diagnostics, archaeometry, materials' characterization) and the application of scientific methodology in conservation enforced objectivity. The relatively unbalanced contribution of science in '*resolving dramatic conservation problems*', or in other words the tendency to '*keep away from the dangerous domain of practical conservation*' (Vaccaro *et al*., 1996, p. 427), was criticised in the conservation literature, as was the damage caused by the unjustified sense of the superiority of technology, and as a result the '*modernization*' of materials and processes without accurate scientific justification (Vaccaro *et al.,* 1996, pp. 426). Hence, the need to '*develop conservation processes and materials and test them by application', as* proposed by Pye (2001, p.180) as a prerequisite for their successful implementation in conservation, is reasonable.

1.2 Scope and Contribution

The history of conservation demonstrates that attitudes have changed, and the modern conservator has little in common with his/her predecessors. The development of a scientific methodology replaced the empirical knowledge of the past. Imitative conservation was followed by the purism movement, which

[4] The concept of *ideal state* has been a milestone is conservation theory and decision-making methodology. It is defined as a past, evidence-based state of an artefact that best represents its values (Appelbaum, 2008).

afterwards gave way to minimalistic approaches towards conservation[5]. We are experiencing the post-minimal conservation era, where there is greater acceptance of virtual restoration. Nevertheless, the latter has been criticized as being largely a substitute for the proposed intervention, and not an active tool that takes part in conservation operations, which are not only the most demanding field but also the one that has received in general the least contribution (Ashley-Smith, 2000). Consequently, practical techniques should be developed, which meet the needs of complex treatment dilemmas, and bridge the gap between pure scientific knowledge and useful solutions, achieving *hi-tech* conservation[6] with high-efficiency results (Munoz-Vinas, 2005).

This thesis builds on these ideas, and assesses computer applications in conservation methodology. It introduces the concept of conservation virtualization in an attempt to provide advanced digital analogues to traditional techniques, which overcome the deficiencies and problematic aspects of conservation methodology. It aims to demonstrate the contribution of digital technology by emphasizing individual aspects of conservation practice, including recording and documentation, examination and investigation as well as remedial treatment. It attempts to provide an insight into the relationship between traditional approaches and computational tools, as well as between the physical, virtual artefact and the conservator. All the methodologies under discussion are restricted to the use of non-invasive techniques, which are in accordance with contemporary museum standards and conservation ethics, and meet the needs of conservation objectives.

The scope of the thesis is the enhancement of conservation methodology through virtualization; meaning the (1) development of computational imaging techniques for enhanced examination and visual analysis, (2) assisting interventive treatment with 3d modelling and 3d reproduction techniques and (3) supporting conservation documentation via workflows and virtual

[5] For a discussion about the history of conservation see, for example, Conti (2007) and Keck (1996).
[6] The term *hi-tech* conservation was introduced in conservation literature by Munoz-Vinas, closely related the use of *a large amount of resources for the conservation* of specific object (2005, 203).

reconstruction. This thesis answers two key research questions: does conservation virtualization: actually exist, and if it does, is it acceptable? There is an obvious parallel with the edited volumes '*Reversibility: does it exist?*' (Oddy and Carroll, 1999) and '*Restoration: is it acceptable?*' (Oddy, 1994). Now, almost two decades after the publication of these volumes, society and the cultural heritage sector have changed. New ideas emerged, and conservation has achieved a more mature level of development, especially in terms of the available technology, as recent advances have revealed new horizons and propelled new applied conservation research. Revisiting these research questions from a contemporary perspective, using novel technologies, is crucial, because the same ethical background is the guiding principle for the development of new conservation practices.

This thesis brings together knowledge from conservation theory and practice, as well as expertise from the fields of computer visualization and imaging. The contributions are not limited to conservation, but intended to be relevant to the cultural heritage sector in general, including artefact studies and museology. The contributions are also relevant to the field of archaeological computing. This research goes beyond the typical limits of archaeological computing, such as appreciation, virtual reconstruction, computational analysis and replication, as it aims at a transformation of original archaeological material in the physical world, not only in virtual environments. There is also a contribution in the area of computer applications via the development of novel imaging and digitization techniques. Considering the high level of complexity of artefacts and their conservation needs, computer applications in conservation practice is an area of research with great potential for the further development of computational methodologies, which can potentially be applicable in other scientific fields as well.

At a theoretical level this thesis contributes to conservation by providing a summary of the main problematic aspects of practice and conservation dilemmas, including preventive conservation, recording and documentation, visual analysis and interventive treatment (section 2.2). Moreover, it presents an overview of the current state of research and practice in the field of digital restoration, digitization, computational analysis and documentation in conservation (section 2.3). This overview is missing from the conservation

literature, even if there is a long list of publications focused on individual aspects of the methodology.

Also, it provides a review of the published work for digital capture techniques (Chapter 3), including the imaging in the visible (section 3.2), infrared and ultraviolet spectral region (section 3.3.1), as well as radiography (section 3.3.2), 3d visualization (section 3.5) and volume rendering techniques (section 3.4), not limited to their straight application, but also covering synergistic approaches to digital capture of artefacts (section 3.6).

It critically approaches the digital capture techniques, and provides a comparative analysis based on conservation needs (section 4.3.1). Undiscovered areas for improvement and problematic aspects are defined, leading to a list of proposals for the development of low-cost and easy techniques, with a particular emphasis on conservation objectives (section 4.3.2). Because computational tools are not designed to deal with the complexity of conservation needs, the aim is to propose necessary transformations and develop new methodologies, able to provide solutions to conservation dilemmas and answers to technological problems. Moreover, this thesis presents a critique for the potential of virtual and physical artefacts, covering the contradictory issues of debate for their use in conservation (section 4.2.1). The implementation of novel mixed-reality approaches in conservation is also proposed, in order to bridge the gap between virtual reality and the physical world, and overcome practical conservation problems (section 4.2.2). The proposed techniques are mapped on RIP schemas, and their potential to alter the dynamics of conservation is clearly defined (section 4.5). Enhanced 3d strategies and systematization approaches for conservation documentation are presented (section 4.4).

At the experimental level the proposed methodologies are applied to a carefully selected, complex, highly deteriorated and demanding group of artefacts, covering a variety of material and artefacts types (section 5.2). An evaluation methodology is designed and implemented, so as to reach safe conclusion about the efficiency of the novel methodologies tested. The key research question is the ability of the proposed enhanced digitization and imaging techniques to facilitate virtual visual analysis (Chapter 5). The latter is the first step towards the virtualization of conservation, which is extended to

the virtualization of remedial treatment, with the experiments dealing with fragment matching, replacement of lost material and re- de- restoration case studies (Chapter 6).

The main contributions at the experimental level are the evaluation of virtual visual analysis and the virtualization of remedial treatment. The former is facilitated via the development of new methodologies such as the microscopic, multispectral, trans illumination and irradiation reflectance transformation imaging (RTI) (section 5.3) and photogrammetry (PG) (section 5.4). This experimentation includes the design of new devices for data capture (section 5.3.1.1.1) and the application of an evaluation framework (section 5.5). Although the standard RTI and PG methodologies are increasingly being used in cultural heritage, no attempt has, to my knowledge, been made for any type of formal evaluation as far as the benefits for conservation are concerned. This is a significant drawback in the understanding of the limitation of the techniques, their development and successful implementation in conservation practice. This thesis aims to overcome this deficiency, gain a better understanding of the abilities and limitations of the techniques, and consequently lead to their broader appreciation and more focused applications.

The virtualization of remedial conservation (Chapter 6) is focused on three common conservation operations; the fragments' identification (section 6.2), gap-filling (section 6.3) and de- re-restoration (section 6.4). The alternative gap-filling methodology proposed is facilitated via the 3d digitization and virtual reconstruction, followed by 3d printing. In that sense the whole restoration process can potentially be transferred to a virtual environment, indicating a significant step towards preventive conservation, eliminating the risk of handling and manual operations, while at the same time it provides advanced options for conservation decision making. The re- and de- restoration case study is included in an attempt to approach conservation decision making virtually. The framework, derived from conventional conservation treatment transferred to a virtual conservation laboratory, is a novel approach not tested before in the numerous virtual reconstruction case studies presented in the literature. Similarly, the comparative analysis of digital and manual execution of conservation operations has never been explored, even if computer

scientists have achieved many developments in the field of digital refitting and automatic fragments matching, using as case study demanding problems and iconic artefacts. The comparative analysis of digital refitting for digital fragments matching and traditional fragments identification for manual fragments matching does not have as its goal the comparison of the outcomes. It is well known that the same result can be achieved both manually and digitally. On the contrary the scope is to compare the processes themselves. Focusing on the methodological aspects in such experimentation can potentially enhance our understanding about the interrelationships between the physical and virtual objects and the conservator. In order to achieve this goal, the use of semi-automatic fragments matching is preferred instead of digital refitting algorithms. The methodological comparison is not restricted to the fragment matching methodology, but also includes the documentation strategies for both virtual and physical operations.

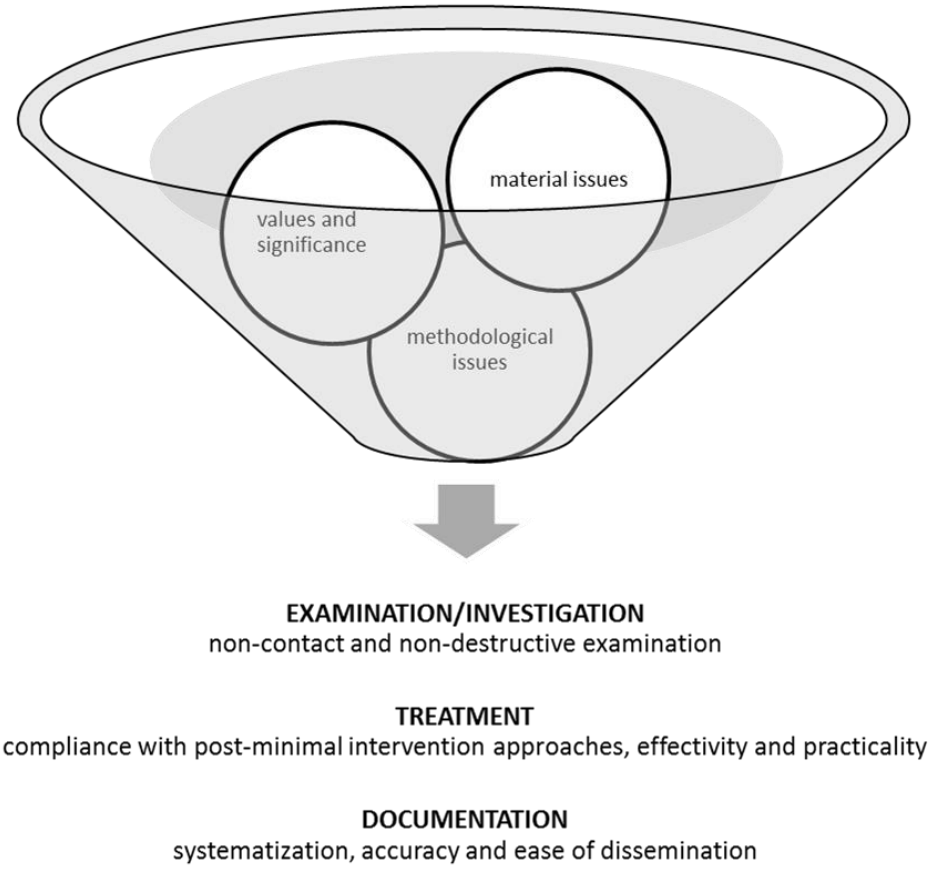
1.3 Computing and conservation practice

In conservation the main contribution of archaeological computing has been the visual representation of objects, for recording, documentation and dissemination as well as virtual reconstruction. Although these are considered to be valuable contributions to the field, many issues have not been yet addressed. Informational preservation has been the focus of computer application and no attempts have been made towards the virtualization of conservation. The only practical operation which has been explored so far is fragments matching, which due to computer constraints cannot fulfil the conservation requirement of practicality (see section 2.2.2.2 for a discussion about fragments matching problems and section 2.3.2.3 for a literature review on digital refitting). Considering the high level of complexity of artefacts and their conservation needs, computer applications in conservation practice is an area of research with great potential for the further development of computational methodologies. It should be considered as an action of respect towards the remnants of the past, which encapsulates the notion, the ideas and the vision of contemporary conservation theory.

The main reasons to include digital applications are relevant to a broad area of conservation practice, such as visual analysis, decision making and treatment

proposal, conservation intervention, documentation and dissemination (Graph 2). The following list summarizes the demands of conservation practice.

- Efficient and affordable examination techniques as the complexity of artefacts cannot be dealt with effectively using conventional approaches
- Limited human-object interaction due to the fragility of artefacts
- Justification and testing of treatment proposal in accordance with conservation practice
- Development of better interventive treatment methodology able to overcome the deficiencies of conventional approaches
- Systematization as the discipline matures, novel treatment methodologies are developed and new schemes for digital documentation for artefacts and processes have emerged.



Graph 2: Correlation of conservation problems to needs (Graph author's own).

In the following sections, areas of conservation practice with particular interest for the present thesis are introduced and the potentials of 3d technology are presented.

1.3.1 Visual analysis

Undoubtedly visual analysis is a milestone in conservation practice, which seeks to provide data relevant to structure, materials and manufacture, damage and use of the object (Fell and Watson, 2008). Any ineffectiveness may have an impact on the material and its integrity, by enforcing inappropriate conservation decision making, which may eventually lead to misinterpretation of the object. Optical microscopy, hyper-multispectral imaging and radiographic techniques are the most common visual analysis tools (Caple, 2006; Fischer and Kakoulli, 2009; Biek, 1963; Lang and Middleton, 1997)

The inadequate preservation of artefacts, their fragility and often their uniqueness and rarity, result in strict museum policies towards human-object interaction, and hence limited access to the archaeological and/or historical evidence for researchers. Conventional visualization methodologies cannot meet the level of detail required for conservation visual analysis. Hence, there is a clear need for the development of non-contact and non-destructive examination techniques, able to facilitate effective virtual visual analysis.

Although visual analysis tools contribute in the examination of the artefacts, they lack adequate three-dimensional representation, one of the most crucial aspects for the perception of objects. A characteristic example is the case of radiography (section 3.3.2), which is the most rapidly advancing technique in the field, able to provide 3d solutions via the use of 3d tomography, one of the most valuable tools for the examination and investigation of objects (section 3.4). Nevertheless, 3d alternatives for microscopy and multispectral imaging able to assist conservation are either at an early stage of development or rarely used. For example, microscopic examination, considered as the eyes of conservators (Oddy, 1982), is largely affected by the correct perception of three-dimensionality. During stereomicroscopic examination in increased magnification, a significant reduction in the depth of field is observed, leading to a false two-dimensional effect, which does not represent reality (Caple, 2006). Also, lighting is important in visual analysis and in particular in

microscopy, as directional light emphasises texture and enables better appreciation of a material's appearance. Brill states that

> "*Normal light illumination exists when light beams of equal intensity are incident onto the surface at more or less a right angle. No textual shadows appear in this light…..if light is projected across a surface, textures cast shadows and show sharp relief*" (Brill, 1980, p.101).

A potential solution would be the use of 3d microscopes, primarily used for biomedical imaging, but in practical terms it is impossible due to the high level of expertise required, the cost and computational power necessary to process the datasets. Three dimensional microscopes are high technology equipment and can only be found in specialised centres. In many cases the sample needs to be prepared in advance. From the above it becomes obvious that the state of 3d microscopy research cannot provide solutions to the perception of three-dimensionality at the microscopic level for conservation purposes at the moment. This is a field of great potential for conservation, and future research may potentially lead to useful discoveries. The need for experiencing the third dimension also applies to other visual analysis tools, such as multispectral imaging. Nevertheless, the research toward the development of 3d multispectral approaches is limited.

Advanced digital analogues of traditional non-digital techniques can assist in examination and analysis of materials, as well as in condition assessment. Their contribution in the perception of three-dimensionality of objects is practically indispensable (Table 2). In the visible range spectrum, computational imaging can provide valuable information about surface morphology, such as tool marks, alterations-anomalies of the surface, remnants of organic materials, unrecognisable decorative features and composition. Moreover, they can be used for the examination of modern additions and for condition monitoring, in order to study alterations to the artefacts, degradation mechanisms and past conservation treatment effects. Beyond the visible, the application of multispectral computational imaging enable the enhanced exploration of hidden features, while nuclear and computed tomography are powerful techniques for an in depth analysis of volumes and inner structure of artefacts.

Table 2: Non digital, 2D digital capture techniques and 3D analogues.

NON-DIGITAL	2D	3D
Drawing Film photography	Imaging	RTI Photogrammetry Laser scanning
Film multispectral photography	Hyper-multispectral imaging	Multispectral RTI Multispectral 3D
Film radiography	Radiography	Computed Tomography, Nuclear Tomography

The use of these technologies in conservation practice is presented in section 2.3, following a detail analysis in Chapter 3. The novel developments of these techniques proposed in this study are presented in section 4.3.2, and their application and evaluation in Chapter 5.

1.3.2 Decision making, treatment proposal and intervention

Because of the nature of conservation intervention, dilemmas are common. In this research the following contradictory matters of scientific debate will be considered:

- preservation versus use

One of the main conservation objectives is providing access to artefacts for those who can benefit from them, both the academic community and the public. However, this use may lead to alterations and sometimes irreversible damage. Following a strict preservation strategy for museum collections can ensure their long-term stability, but simultaneously will isolate them from people, limiting their use for the present generation while securing their material integrity for the future researchers and museum visitors (for a discussion see section 2.2.1).

- de-and re restoration dilemma

The removal of previous treatments is a risky operation. The potential benefit of re-treatment should be taken under consideration without underestimating the significance of the previous restoration for the object's biography, even if it is not appropriate by contemporary museum standards (for a discussion see section 2.2.2.5).

- re-treatability

Interventive conservation treatment alters the appearance and the chemical properties of the object. The reversibility of such treatment and the future re-treatability of the object is a practical and ethical dilemma for conservators.

- restoration operations

Restoration operations such as joining, reshaping, gap-filling and retouching are among the most controversial processes of conservation. Their execution has been a matter of scientific debate and their 'acceptability' still remains under discussion (see section 2.2.2).

In addition to the already briefly mentioned ethical dilemmas there are a number of challenging practical issues for conservators in the area of preventive conservation (handling, storage and replication), remedial conservation (investigative cleaning, autopsies, micro-excavations and fragments identification) and restoration (joining fragments, gap-filling and retouching). Conservators seek to find the best approach in order to ensure the preservation of the object, without diminishing its research value and possible uses, taking into consideration any evidence, material and non-material. The conservation decision making is of equal importance to the treatment itself, and a most challenging task which demands objective judgement.

During this stage 3d technology can assist in reaching a compromise in the case of complicated research projects. Computer graphics can test hypotheses and assure the most appropriate treatment. Furthermore, they can justify treatment proposals, in case of demanding projects, considering that the advances of computer graphics made ultra-realistic visualization possible. During conservation digital technologies can monitor and test operations in order to avoid irreversible damage. Less attention has been devoted to the incorporation of digital tools in conservation practice, which can potentially lead to enhanced conservation treatment, and overcome some practical limitations of traditional approaches in accordance with ethical requirements. In the future computer graphics and 3d printing technologies will probably represent and reproduce reality even more accurately, and their implementation will be more affordable and popular. These problems are analysed in Chapter 2 along with their digital solutions.

1.3.3 Conservation Documentation

Conservation data and experience sharing, presentation and dissemination by means of appropriate and informative forms of publicity are crucial issues for conservation documentation. Such reports are of great importance for the preservation of cultural heritage and for the development of conservation science and practice. Data relevant to past conservation operations should be retrieved. Condition reporting and, if required, re-restoration of artefacts is more effective when accompanied by appropriate documentation of previous restoration. Issues related to condition monitoring and comparison as well as materials compatibility can be examined, conclusions for past conservation strategies, materials and equipment used can be recovered.

There is a clear interest in the study of the museum lifetime biography of independent artefacts and specific collections, as well as the study of the development of conservation strategies. Open source science, workflows and provenance graphs, as well as the use of advanced technologies that enable easy online data sharing can improve common practices of archives research, documentation and dissemination-presentation of conservation projects. In particular, the adaptation of the techniques already mentioned will provide faster, up-to-date and more effective retrieving of trustworthy and meaningful data. Dissemination and presentation of data will become easier and faster. The ability of such technologies to safeguard data, in order to avoid dissemination of inappropriate, misleading, illegal or unauthorised information, is also worth mentioning. Considering the multidisciplinary nature of conservation, and the involvement of experts and researchers derived from different disciplines, co-operation is fundamental. The potential scientific co-operation automation provided by workflows in addition to the preservation of digital records and their provenance can improve documentation practices.

Conservation documentation is discussed in section 2.2.3, including the ethical and legal background (section 2.2.3.1) current practices (section 2.2.3.2), problematic aspects (section 2.2.3.3) as well as the major issue of digital preservation (section 2.2.3.4). The potential of digital technology for documentation purposes is discussed in section 2.3.3. Proposals for computer visualization for conservation documentation purposes, provenance and

systematization are presented in section 4.4 and are evaluated in Chapters 5 and 6.

1.4 Chapter outline

This thesis is divided in two parts. Part one presents the digitization and imaging approaches currently in use in conservation practice, and part two presents and evaluates the digital conservation methodology proposed. An outline of the thesis is provided below.

Part one: Current digitization and imaging approaches

Chapter 1: Introduction

Chapter 1 is an introductory chapter, which presents the aims, contributions and structure of the present research. It provides the reader with the necessary background information and discusses technological problems and ethical issues raised, underlining the needs for the development of an enhanced methodology.

Chapter 2: Digital technologies and conservation practice

Chapter 2 presents the problematic aspects and dilemmas in conservation regarding the three basic types of conservation treatment, interventive conservation, preventive conservation and restoration and conservation documentation. It then discusses digital technologies used to overcome these problems.

Chapter 3: Digital artefacts capture

Chapter 3 focuses on techniques for digital capture of texture and colour, beyond visible, 3D and volume data. The requirements, technical background and applications of each recording strategy are examined, along with the proposed synergies in the published bibliography, providing an overview of the digital capture of artefacts.

Part two: Evaluating and enhancing digital conservation

Chapter 4: Introduction to part two

Chapter 4 investigates the interactions between virtual and physical artefacts, and identifies areas requiring improvement and gaps in digital processes regarding digital capture and documentation. It proposes novel methodologies for digital capture and explores the implementation of mixed reality

approaches in conservation. It then maps the proposed techniques in RIP schemas so as to define the methodological changes proposed.

Chapter 5: Virtual visual analysis

Chapter 5 describes the experimental procedures for RTI and PG data capture and processing and evaluates the techniques based on the results on selected material studies.

Chapter 6: Virtual and physical reconstruction

Chapter 6 presents a methodological comparison of the manual process for the identification of fragments and joining and the digital process for virtual reconstruction. It investigates conservation decision making and restoration of incomplete artefacts via digital strategies.

Chapter 7: Conclusions and recommendations for further work

Chapter 7 summarises the experimental findings and reaches conclusions regarding the application of digital techniques in conservation. It addresses the issues discussed in the whole thesis, and proposes a new methodology for the study and conservation of artefacts. It then indicates the future directions of research in the field.

Chapter 2: Digital technologies and conservation practice

2.1 Introduction

In the field of conservation virtual restoration has been criticized as being largely a substitute for a proposed intervention but not an active tool in conservation practice (Ashley-Smith, 2000). The application of digital reconstruction in conservation is discussed in this chapter, in order to draw attention to the new strategies, enriched with computational tools, which provide practical solutions and overcome the disadvantages of traditional techniques. Three-dimensional technologies can potentially play an actual role in interventive conservation treatment, restoration and preventive conservation.

In the following section contemporary preventive conservation measures, remedial conservation and documentation approaches are presented, emphasizing the problematic aspects of practice. Technological needs are also discussed, as well as the potential of digital technology to overcome these problems.

2.2 Conservation problems and dilemmas

2.2.1 Preventive conservation

Prevention includes managing risks, undertaking steps so as to prevent or minimise the possibility of undesirable future states (Ashley-Smith, 1999). Historically the attitude towards preventive conservation has changed in accordance with museum and research practices. During the nineteenth and the beginning of the twentieth century protection measures were limited. Between the 1930s and the 1990s ideas of safe handling evolved. Although the guiding principle is that the objects should be subjected to the minimum of handling (Organ, 1968), changing views about the role of the museum and their relations with communities suggest that there is a clear demand for closer public interaction with the collections. The value of collecting and

safeguarding artefacts is respected, but the artefacts and their educational value is not the fundamental role of the museum. It is the *'spaces, artefacts, visitors, and its place embedded within popular culture'* that form the museum experience and reflect the ideas and notion of New Museology (Stephen, 2001, p.298).

Touching is considered as the most important interaction between humans and objects (Paterson, 2007).

> '*We need touch to understand objects in three-dimensional space, and to fully appreciate an object we are required to handle it… Combined with our other senses, we are able to understand the objects in a way that we would not have been able to understand by sight alone' (Butler and Neave, 2008*, p.133).

Based on the above, there is a growing need for handling collections and closer interaction between visitors and artefacts (Figure 1). The advantages of handling objects have been discussed in the literature, including '*The Power of Touch: Handling Objects in Museum and Heritage Contexts*' (Pye, 2007) and the '*Touch in Museums: Policy and Practice in Object Handling*' (Chatterjee *et al.*, 2008). Museums' policies towards interaction with the collections have been criticized in a number of articles (Candlin, 2004; 2006). The main advantages of handling, based on Walker's research (2013), are the enhanced learning and understanding of objects through touch, enabling also self-interpretation and bringing down barriers. Moreover, the handling of ancient or historic objects is a unique experience that connects us to the present and the past, and promotes a sense of respect for the material culture of past civilizations (Walker, 2013, pp.144-146). In addition to handling collections and closer public interaction with objects there is now a growing number of travelling exhibitions (Caple, 2011). Consequently, the need for careful handling and development of alternative approaches for accessing the objects are pressing.

Figure 1: Handling session at the University of Oxford museums. Available from: http://www.museums.ox.ac.uk

Parallel to the hands-on museum movement (Caulton, 1998), the hands-off conservation movement and the ideas of preventive conservation emerged. As a result of this paradox, controversial opinions towards interaction with artefacts appeared and the preservation-versus-use debate emerged. Moreover, the appreciation of handling collections and their more intense use in museums makes the handling of objects a timely issue which highlights the dilemma of preservation versus use. Even before modern conceptual schemas arose, codes of ethics discussed the balance between the social need to use the artefacts and their preservation. Scholars underline the vulnerability of museum collections to mishandling (Costain, 2011), and note that the consequences may be either complete loss or minor repairable damage. Moreover, they emphasize the potential loss of evidence due to improper handling (Miles, 2011). Contemporary museum standards are directed towards avoiding damages from handling, by recommending limited physical interaction, especially in the case of vulnerable artefacts, in order to forestall deterioration. Conservators try to avoid the obvious risk from physical interaction with artefacts as much as possible, particularly for objects in a poor state of preservation and/or vulnerable material types. For that reason, handling objects should be considered only when it is necessary. Manuals have been published by cultural organization (Pouliot *et al.*, 2013; Shelley, 1987) and training sessions are provided, including e-learning tools (Museum of London, 2013) (Figure 2).

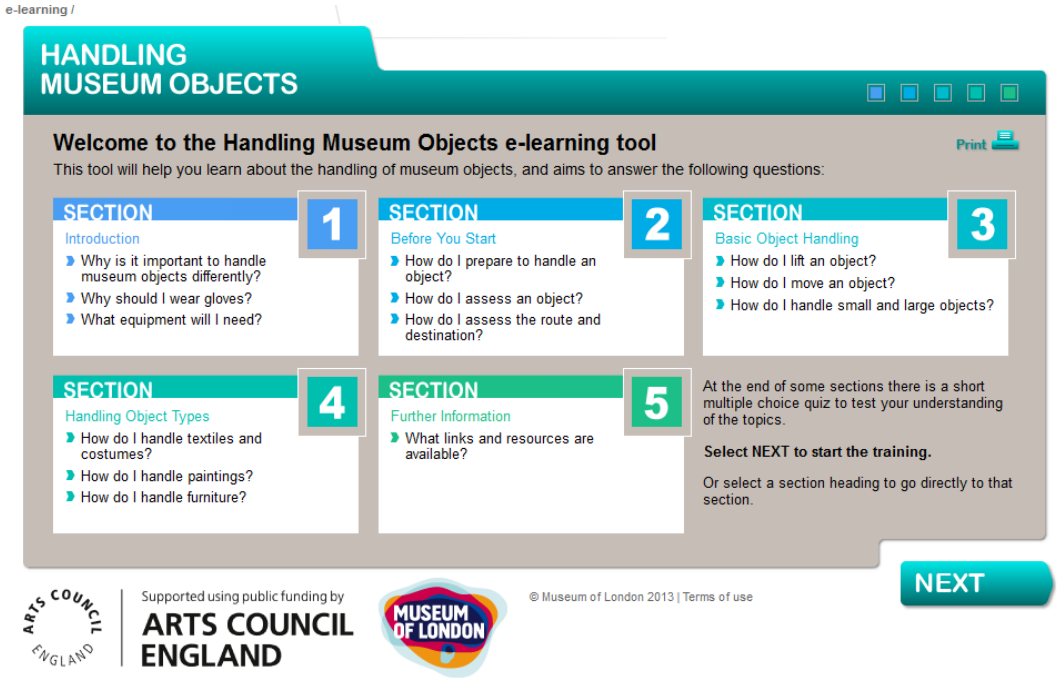


Figure 2: Handling Museum Objects e-learning tool, welcome screen (Museum of London, 2013). Available from: http://www.museumoflondon.org.uk/Resources/e-learning/handling-museum-objects/

It is conservators' duty to provide access to artefacts so that they can be used by scholars and the public, but Ree (2009) reasonably states that

> '*there is no point in keeping collections immaculate if you do not let anyone consult them, but you cannot do without exposing them to conditions that are liable to damage them and curtail their lease of life*' (Ree, 2009, p.3).

Almost a decade earlier, Uprichard, a conservator from the British Museum, commented on this issue by stating that

> '*if the only function of the museum is to preserve collections, we'd have put them in a room, we'd lock them in a controlled environment and throw away the key*' (Candlin, 2004, p.76).

This scenario has not been the conservators' choice so far, as they deeply appreciate the need to use collections, and see accessibility as one of the four major conservation objectives.

The advantages of handling should not be overlooked for the sake of long term preservation of artefacts, but there is a need for careful, purposeful handling. Even after training, handling is not possible for fragile and rare museum artefacts, as it threatens their material integrity and may cause irreversible damage[7]. An alternative solution, when originals are not available or cannot withstand handling, is the use of replicas. Replication is a common practice for the protection and safeguarding of the original artefacts. It has been proposed as a means of preservation for safe storage and display of fragile objects. The best approach in cases of challenging preservation, such as uncontrollable environmental conditions and extremely bad conservation states, is to record, copy and store securely the replica or to replace the original with the replica (Caple, 2000). It is also worth noting that the visual or written records are responsible for the preservation of a vast amount of knowledge from previous generations. Thanks to reproductions of artefacts, information related to cultural heritage has been saved after natural disasters or wars. Replicas have been proposed as an alternative to restoration, and in that sense they support the ideas of minimum intervention (Pye, 2001). Their value also goes beyond the scope of preservation, as replicas contribute significantly in education, archiving and recording. Worth mentioning is also the strong commercial interest for replicated museum objects. Traditional moulding and casting techniques used for the preparation of reproductions may potentially harm antiquities, as they require contact with the original material. In practical terms, their application to fragile artefacts is a demanding and time-consuming process that exposes artefacts to risk, even if protective facing is applied. The use of various tools and equipment may scratch or mark the surface, dislodge or remove pieces.

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[7] However, it is well known that touching artefacts is not the only museum practice that may have damaging effects on objects. For example, studies have proved that museum lighting is responsible for degradation, both thermal and photochemical. For this reason research pointed out adequate lighting strategies so as to provide the necessary lighting for the appreciation of artefacts without causing damage (Schaeffer, 2001; Druzik, 2004).

The available digital tools for safe interaction with artefacts are presented in section 2.3.1, where the use of informational preservation in conservation via 3d digitization and printing are presented, as well as in section 2.3.4, where mixed reality approaches, such as haptics, tagging and projections are examined. 3d printing is discussed in section 2.3.2.5 and digitization techniques are presented in Chapter 3.

2.2.2 Remedial conservation

Conservation is grounded on the interaction between the artefact and the conservator. No cultural heritage discipline is more physically close to artefacts than conservators of antiquities and works of art. Although interaction with objects is a fundamental part of archaeological and historical research in general, including discovery, study, analysis and exhibition, it is the conservator that has the privilege, or sometimes the curse, of physically interacting with objects at a level not achieved by other museum professionals, both qualitatively and quantitatively. This is not only because the conservation operations involve lengthy interaction with objects, considering that conservation is a time consuming process, but also because this interaction introduces alterations, either on the appearance by cleaning operations or in the composition of artefacts by applying consolidation.

Also, conservation is a multisensory process. During investigation the conservator not only examines the object visually, but also uses tactile interaction in an attempt to explore its condition and its needs, and identify evidence of manufacture and use. There is a long list of properties of materials and objects that can be assessed through touch, using either hands or hand tools, such as temperature, moisture or dryness, stickiness, waxiness, resilience and texture. Moreover, irregularities, flaking and powdering surface, density and weight informs us about the objects condition (Pye, 2004). Organ (1968, p.11) reasonable states that '*tactile sense is in such common use that its sensitivity is seldom brought to notice*'. Even if the tactile interaction during examination can be omitted, it is inevitable in remedial conservation treatment and restoration, for example during cleaning, joining, and gap-filling and

retouching. The success of such operations lies on the skills of conservators, as well as their knowledge, to make decisions and solve dilemmas.
The alterations introduced to the material aspects of the artefact, as a result of conservation processes, suggest a qualitative difference between the conservator's interaction with artefacts and other museum specialists and the public. Conservation is not just an experience, as is the public's interaction with artefacts. It is not only a critical appreciation of the artefact, as is the archaeological and material culture approach. Conservation goes one step further by applying changes to the artefact itself intentionally, so as to preserve material evidence, safeguard aesthetic integrity and investigate the biography of the artefact.

> '…*For if historians can revise their diagnoses and value judgements at any moment, the formulations of which remain entirely discursive, the conservator, on the contrary has always to carry out his decisions on the object itself'* (Philipot, 1983, p.227).

Indeed, reversibility is impossible in practical terms. According to Smith (1999, p.9) '*in a minefield of ethics, philosophical debate and professional practice'* reversibility is '*an unattainable ideal'* while for Schinzel (1999, p.43) it is '*Utopian…a paradigm of paradox… an illusion'*. In that sense removability or re-treatability are proposed instead of reversibility (Appelbaum, 2007; Munoz-Vinas, 2005).

The problematic aspect of common conservation and restoration operations, such as autopsy, micro-excavation and investigative cleaning, gap-filling, aesthetical restoration, fragments matching and the de- re- restoration dilemmas are presented in the following sections.

2.2.2.1 Investigative cleaning, autopsies and micro-excavations

Archaeology has gained a vast amount of information by applying processes such as archaeological autopsy, micro-excavation and investigative cleaning[8]

[8] These are operations that are similar in nature although differing considerably in scale. Excavation can be considered as a similarly destructive, non-reversible process, too.

(Figure 3). At the same time their destructive, non-reversible interventionist character should not be neglected (Figure 4-5). Even when highly skilled professionals are employed, following appropriate tools and techniques for these '*micro-archaeology*' operations, including careful recording, mechanical controllable means and additional stabilization, this type of operation may endanger the materials integrity, especially for fragile materials of an organic nature or highly deteriorated ones (Cronyn, 2003, pp.63-64). Apart from the high risk of such operations, another disadvantage of this practice is that the whole process is time consuming, and expertise is needed for judgement and decision making. It is important to stress that in many cases conservators come to the disappointing conclusion that these difficult and risky operations were unnecessary because of the quality of the findings. Hence, there is a demand for alternative non-destructive, reversible, safe cost- and time-effective techniques for the execution of archaeological autopsies, micro-excavations and investigative cleaning.

Figure 3: Block of soil lifted from excavation (Image author's own).

Figure 4: During micro-excavation (Image author's own).

Figure 5: Tools used for micro-excavation (Image author's own).

See section 2.3.2.1 for the use of 3d tomography for enhanced investigative operations. In addition, digital capture techniques (Chapter 3), such as capturing volume (section 3.4) and data beyond the visible (section 3.3) are useful for digital micro-excavation and non-invasive inspection of artefacts. In Chapters 5 and 6, the case studies presented, demonstrate the efficiency of the proposed methodologies.

2.2.2.2 Fragments identification

It is common for archaeological material to survive in a deteriorated condition, fragmented and incomplete. A fracture may have taken place intentionally in antiquity, at a time when the object was destroyed or not useful anymore, or unintentionally, for example because of physical disasters. Fracture is a result of normal material degradation when buried, especially in cases of fragile materials. Apart from the ancient fractures, objects may break during excavation or transportation to the museum. This phenomenon is less common now, but unfortunately the human factor remains an agent of deterioration, considering the changes introduced to the artefacts' environment by excavation.

An object in fragmentary state may be reconstructed, making this process one of the most common remedial conservation activities. There is no doubt that reconstruction is a fundamental part of conservation, and its contribution to archaeological research is of great significance. It throws light on the interpretation of the archaeological site, the determination of its use and the technology of our ancestors. The skills for the successful execution of this process are considered essential. Moreover, although ceramic sherds are the vast majority of fragments for reconstruction (Figure 6), fracture does occur in

all material types, being common for glass, wall paintings, bone and ivory, stone, metal, as well as for archival materials, leather and textiles.

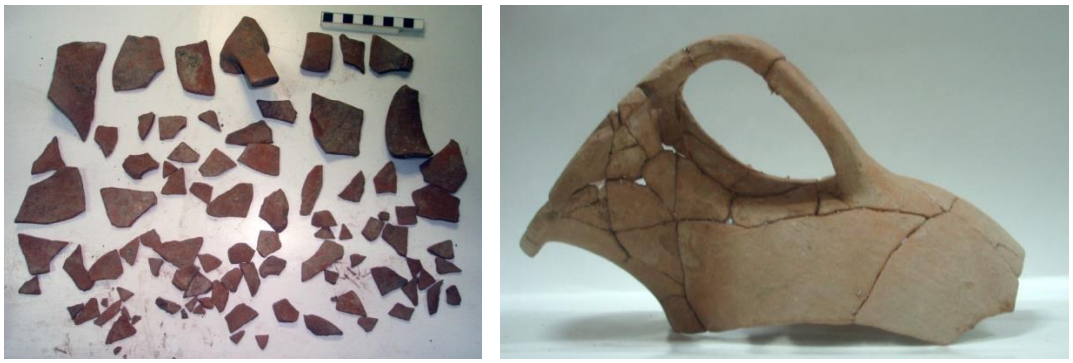


Figure 6: Oinochoe, before and after joining (Image author's own).

Conservators use the excavation data, previous knowledge about known artefacts types, decorative elements, and evidence of manufacture, degradation pattern, geometry, volume and texture of the fragments as tools for reconstruction. This manual procedure for fragments' matching is a painstaking, time- and space-consuming operation, even for dedicated, experienced professionals. Manual search provides sufficiently effective results when the number of fragments is reasonable and the overall condition of the material permits excessive manual handling. In cases with large groups of fragments the results are rather disappointing, considering the time and expertise needed. Further complexity is introduced by the missing fragments.

A literature review on digital refitting research and applications can be found in section 2.3.2.3 and an evaluation of available tools for semiautomatic fragments matching is presented in section 6.2.

2.2.2.3 Gap filling

The replacement of lost material is one of the most crucial operations necessary due to structural and aesthetic reasons. After restoration the object becomes more accessible for research and display. But the process of gap-filling is problematic due to practical and ethical issues, such as the productivity of materials and techniques, long term performance, safety and ethical limitations of restoration. Reconstruction without filling the gaps of the object can be damaging, because of the asymmetrical stress put on the edges, or the physical instability of the conjoined shreds (Cronyn, 2003). Incomplete

objects are usually incomprehensible and not aesthetically appealing, so restoration is inevitable so as to protect their aesthetic integrity, and to make them accessible for both professionals and the public (Figure 7-8).

Figure 7: Pseudocypriote amphora (left) in need of gap filling due to instability (Images author's own).

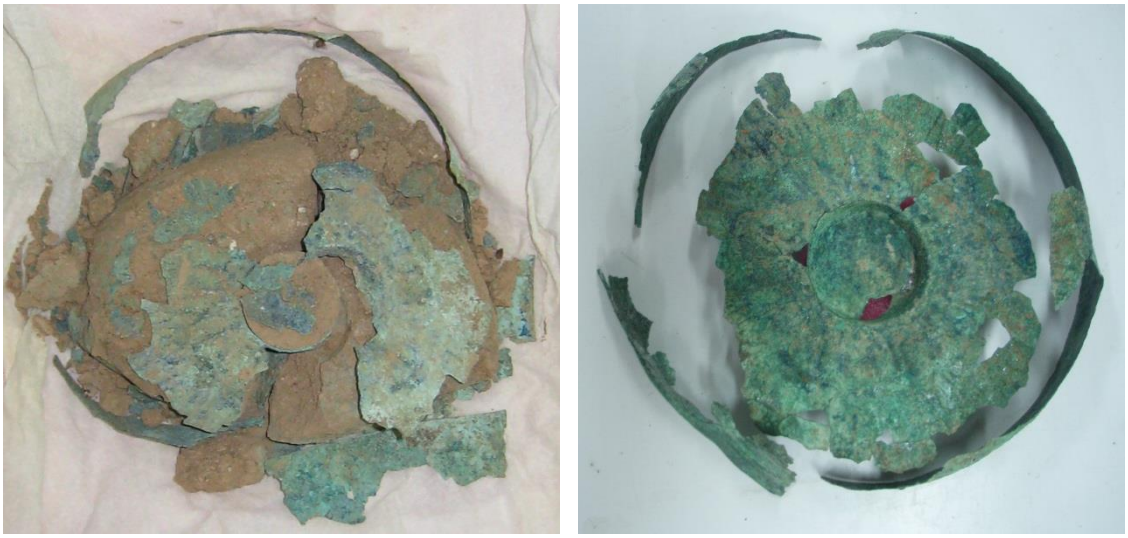


Figure 8: Bronze phiale before conservation (left) and after joining (right). Lost material needs to be replaced for safe handling and display (Images author's own).

The material used for filling should be safe to use, reversible, durable, of appropriate strength and density, capable of modelling or casting and adjustable to the object. It should not be contaminated and not shrinkable after curing or ageing. Their thermal expansion rate must be compatible with the object (Buys and Oakley, 1996). Nevertheless, it is well known that the materials used for such operations may lead to future reconstruction failure. A characteristic example is the deterioration of acrylic and vinyl adhesives, as a result of depolymerisation, oxidation and hydrolysis, under the effect of physical (temperature, pressure, radiation) chemical (oxygen, pollution) and biological (microorganisms) processes, which leads, by means of undesirable reactions, in discoloration (yellowing), white blooming, changes in volatility, solubility, tensile strength and pH, decay, distress (Horie, 2011). Another problem encountered is the bad cohesion between original and filling material, mainly caused by dimensional changes of the filler, accompanied by cracks on the restored gap. Consequently, there is a high possibility of fracture and loss of original material (Figure 9).

Figure 9: Raking light image shows cracks on the filler material and flaking of adhesive on a restored ceramic (Image author's own).

Conservators have analysed the problems encountered and presented the techniques employed for the replacement of lost material in glass (Davison, 2003; Fisher and Norman, 1987; Risser, 1997) ceramics (Barov, 1988; Geschke, 2004; Kariya, 1997), leather (Kite and Thomson, 2006), wood (Grattan and Barclay, 2010; Podmaniczky, 1998) stone (Griswold and Uricheck, 1998; Nagy, 1998) and metals (Lane, 1974).

Traditional methods for filling gaps subject the object to physical and mechanical pressure (Figure 10). Considering the shape of the object, and the condition and type of material, the applications of these methodologies may not be feasible. Moreover, their acceptability in case of fragile objects and vulnerable material types are under question. Conservation science research is directed towards the improvement of conservation materials, so as to overcome the problems already mentioned. In addition, the development of new restoration techniques for gap filling is a prosperous field of research.

Figure 10: During replacement of lost material of a ceramic vase (Image author's own).

3d printing is proposed as an alternative to traditional approaches for gap filling, as discussed in section 2.3.2.5 at theoretical level and in section 6.3 at practical level.

2.2.2.4 Aesthetics of restoration-retouching

Treatment is a compromise between material and aesthetic integrity, investigation needs, display demands, respect towards the historical and archaeological evidence and the authenticity of the object. In painting and retouching are considered as the most challenging conservation tasks because of the controversies and scientific debates over aesthetic restoration. Even if the scientific discussion had examined various methods and techniques, the aesthetics of restorations remain a matter of subjective judgement and debate.

Replaced missing material, without in-painting or non-retouched objects, may be visually distracting and not aesthetically pleasing (Figure 11). For that reason conservators often choose to colour the fills or the damaged areas. According to Elston (1990, p.78), the most crucial aspect of aesthetic restoration is to '*find suitable aesthetic systems that preserve the individual values intrinsic in each case while minimizing disturbing losses*'. To what extent should the in-painted area be adjusted to the surroundings, so the viewer can gain an impression of the original appearance of the object, and clearly discern the authentic part? One of the most widely accepted rules is '*the six-inches six-feet'* (Oddy, 1992, p.11), which comes in accordance with contemporary practice and is followed by major organizations such as the British Museum (Smith, 1998). Any damage repair should be discernible to an observer six inches, but not six feet, away.

Figure 11: Krater after joining and gap filling and before aesthetic restoration (Image author's own).

Nevertheless the degree of in-painting and retouching varies (Figure 12). Usually the restoration is visible to the naked eye on close inspection, but sometimes substitution of fragments and complete re-painting can be seen (Koob, 1998) while many intermediate approaches from monotone shades to close colour matching are exhibited in museums and presented in restoration studies. From the various alternatives of retouching and in-painting, uniform monotone colouring close to the original colour of all the filled gaps, so as to distinguish the filled areas from the original ones, without in-painting chips and break lines or adding any detail of the lost decoration, was preferred in a number of cases, including the red-figure vase of the Benaki Museum. Other available options were to use a lighter tone for the fills so they would stand out more in all areas (Theofanopoulou and Tossiou, 2007). Also in-painting can be used for the elimination of wear. For example, cracks and lacunae in the original fragments of the Kyknos krater in the Metropolitan Museum were filled, levelled and coloured to match the terracotta background (Barov, 1988). More intense restoration approaches include in-painting of decoration features.

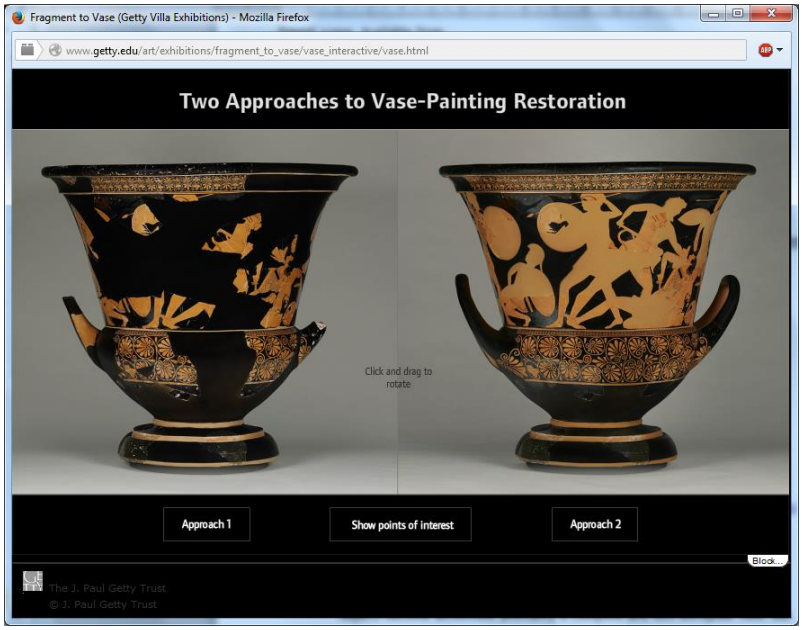


Figure 12: Screenshot of the interactive feature developed at the J. Paul Getty Museum, presenting two different vase painting restoration approaches. Available from: http://www.getty.edu/art/exhibitions/fragment_to_vase/vase_interactive/vase.html

The more the conservator follows interventionist approaches, the more the objects become accessible, providing a complete and less disrupted view, but simultaneously ethical considerations arise, because the intervention should stop when hypothesis starts. Conservators are aware that archaeological - historical evidence as a basis for restoration is required so as to respect the material integrity, the aesthetic values and historical message of the fragmentary authentic material. Even when there is evidence for the original appearance of the artefact the restoration is still challenging, because of the practical problems which arise in replicating lost material, especially when it comes to elegant decorative features. In practical terms the blending of colours and materials so as to resemble the authentic appearance is highly problematic. The artistic skills of the conservator, in addition to the aesthetic restoration techniques, are being used so as to successfully execute such operations. However, the aesthetically pleasing appearance of restorations relies totally on subjectivity, and cannot be considered a result of scientific judgement.

Digital restoration, discussed in section 2.3.2.2 can assist in solving aesthetic restoration problems.

2.2.2.5 Previous repairs, de- and re-restoration

Artefacts, as part of a museum collection, undergo a series of treatments during their existence. Previous conservation and restoration operations or old repairs leave '*marks*' or physical signs of being in the museum, which offer valuable information about the object's biography. They have spiritual or historical significance. At the same time those repairs can be unstable, aesthetically displeasing or even cause damage to the object (Figure 13).

Figure 13: Ceramic plate showing blackening of adhesive and reconstruction failure (Image author's own).

Excavated artefacts have undergone cleaning treatments, either in situ or in conservation laboratories, in order to determine their material and decoration and investigate their typology and dating. A limited number of finds fall in the exception of artefacts buried in unique conditions, which preserve their original appearance up to a certain point. In the vast majority of cases cleaning operations alter significantly the appearance of artefacts, by means of subtraction of encrustations, corrosion layers, dust and other deposition of particles. Simultaneously, deep cleaning destroys data of great importance, such as residues of food in vessels, sensitive organic remains, engravings and inscriptions etc. For example, the archaeological evidence is permanently lost when pottery undergoes chemical cleaning by means of strong acid solutions. Nowadays, semi or fully mineralised organic matter, as well as traces of organics and impressions on metals, especially iron, are subjected to thoroughgoing research. But Caple (2009) reasonably states that previous generations failed to anticipate these techniques, and would have cleaned them, because for them evidence had different criteria. Another example is the cleaning of tinned ceramics, which removed remnants of tin decoration (Figure 13). Recent research dealt with these artefacts in the region of Macedonia, making use of non-destructive analytical techniques in order to determine any

remnant tin (Kotitsa, 2012). Moreover, deep cleaning can act as a positive catalyst of deterioration. Acid cleaning, stripping methods and electrolytic cleaning are responsible for severe damage to bronzes. Even less extensive mechanical cleaning may affect the stability of bronze surfaces. The cleaning of the protective patina of metals re-energises active corrosion on areas which are believed to have acquired a certain level of stability.

Figure 14: TInned ceramic plate, before (left) and after conservation (right), showing the limited cleaning approach followed in order to protect the fragile decoration (Image author's own).

A problem strongly related to the change in conservation practice is the presence of fragments, which belong to the same artefacts in different conservation states. The identification of fragments is a long standing problem in conservation. Sometimes it is impossible to determine the correct positioning of each fragment, or even worse, to group some fragments as parts of the same object. As a result, some fragments are deeply cleaned while others were left in museum store-rooms. Conservators face a practical and ethical dilemma: aesthetics and authenticity versus preservation. For example, a red-green corroded handle on a highly reflective yellowish metal surface is not aesthetically pleasing but it represents the authentic appearance of the vessel. Deep cleaning of the handle in order to suit the vessel goes against ethics and contemporary conservation theory, and has negative influence on preservation.

The expansion of the ideas of minimum intervention in the previous decades found vigorous supporters, and has dramatically influenced everyday conservation practice. In the case of previous repairs, such as gap filling and retouching, the presence of deficiencies, either manufacture mistakes or deterioration effects, is common. Typically those deficiencies are flaking, discoloration, scratches and minor losses or holes in the structure, coarse texture or excessive height. Structural problems mainly derived from bad cohesion between the original and filling material. Dimensional changes of the filler result in cracks on the restored gap and problematic cohesion. Consequently, there is a high possibility of fracture and loss of original material. Sometimes, the filling hides original material, which is not acceptable according to conservation ethics, because it insults the authenticity of the artefact. Another interesting case is the discovery of fragments which belong to already filled areas of artefacts.

Koob (1998) presented a number of materials used for filling large and small gaps in the past, and highlighted the significance of identifying these materials and understanding their properties. First of all, the conservator has to successfully detect the presence of old repairs. Some of them are easily discernible because of the well-known ageing phenomena attributed to materials commonly used in the past, while others are confusing and difficult to recognise using common examination methodologies. For that reason, thorough examination can contribute to successful identification of previous repairs. Ultraviolet fluorescence techniques can be of great help in doing this. Afterwards, phenomena hidden beneath signs should be revealed and identified, in order to proceed to interpretation: to attribute phenomena and signs to instances of artefacts' '*life cycle'*. The proper interpretation of such information contributes significantly to our knowledge and can be of great help for re-treatment decision making. Problematic aspects of re-conservation projects are insufficient documentation, the extent of operations and reconstruction failure.

At the same time, the removal of the unacceptable restoration may be a risky process, due to the application of physical force and the use of solvents (Figure 15). Moreover, even after removal of previous restoration, the artefact will have to face another cycle of operations for gap filling purposes, once again under

physical and chemical pressure. The risk encountered in the removal of restoration and the potential benefit of re-treatment should be taken under consideration, without underestimating the significance of previous restoration for the object's biography, even if it is not appropriate by contemporary museum standards. A characteristic example is the de- and re-conservation of a large jar at the Getty, due to the darkening of old conservation materials (shellac) and the misalignment of fragments (Figure 16).

Figure 15: Removal of aged adhesive using a scarpel (left) and removal of old restorations (right) (Images author's own).

Figure 16: Oil Jar with a Deceased Youth Seated at a Tomb, associated with the group of Huge Lekythoi, about 400 B.C. Details of old repairs. Available from: http://www.getty.edu/art/exhibitions/fragment_to_vase/lekythos.html

The analysis of problems of previous repairs invokes technological needs and raises theoretical and ethical questions, and hints at the difficulty and the level of expertise needed in order to meet the needs of re-treatment projects. There is a need for advanced documentation techniques, enhanced examination and analysis and development of alternative methodologies so as to overcome de-conservation dilemmas. A case study presented in section 6.3 is dealing with

de- and re-restoration problems using advanced digital tools instead of traditional methodology.

Available digital solutions regarding the problematic aspects of remedial treatment are presented in section 2.3.2, where recent developments in the field of 3d tomography, digital refitting, 3d search and analysis and 3d printing are presented along with digital restoration applications. The way these techniques alter the dynamics of conservation is discussed in section 4.5.

2.2.3 Conservation documentation

Documentation is a cornerstone of archaeology, as it is in all scientific fields. Museum documentation is not only concerned with the material composition of objects but also with the documentation of the collecting process, both for museum professionals and the public (Desvallées and Mairesse 2010). Documentation can be understood as an ever growing knowledge activity, based on multidisciplinary cooperation, which consists of research, recording, evaluating, interpreting, correlating, archiving, managing, and disseminating information. In that way the records are valuable tools for monitoring, understanding, and conservation (Addison *et al.*, 2005). In the following sections the ethical and legal background of conservation, the methodologies currently in use and their problematic aspects are presented.

2.2.3.1 Ethical and legal background

Documentation is an obligation which includes the production and maintenance of '*accurate, complete, and permanent records of examination, sampling, scientific investigation, and treatment*' according to the American Institute for Conservation of Historic and Artistic works (1994, p.9). The preservation and sharing of such records and experience is an action which contributes to the growth and progression of the profession to the highest standards by continuing to develop knowledge and skills, as stated in the Code of Ethics and Rules of Practice published by the United Kingdom Institute for Conservation (1996). Besides, documentation, consisting of the accurate pictorial and written record of all procedures carried out during conservation and the rationale behind them, is an obligation for conservators according to major international organizations, such as the United Nations Educational,

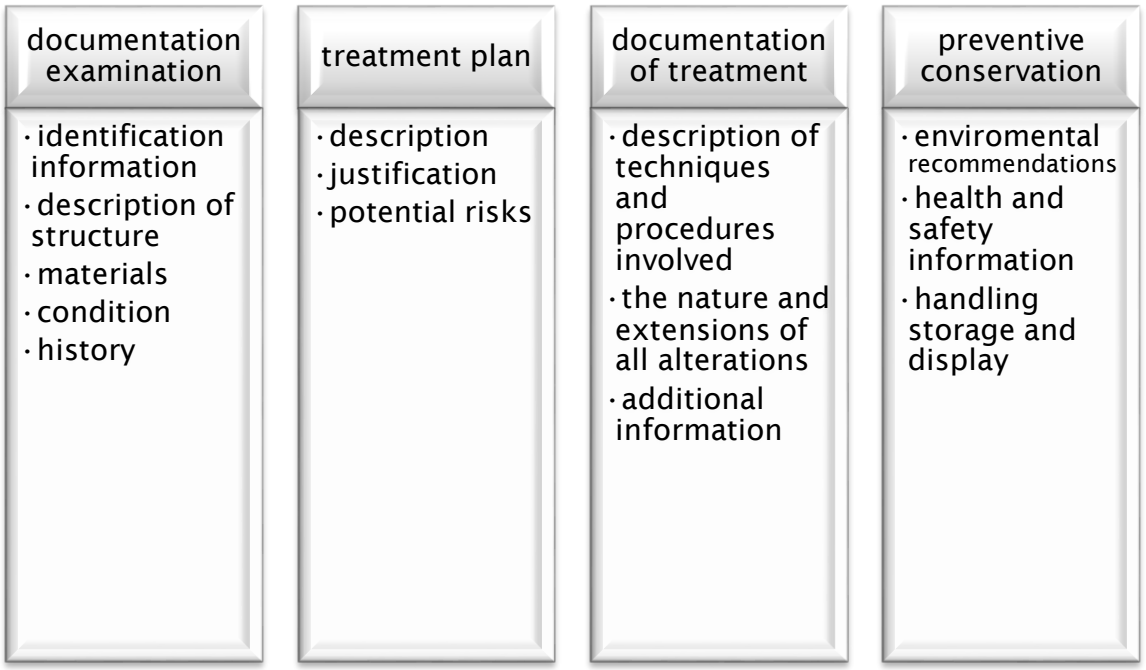
Scientific and Cultural Organization (UNESCO), the International Institute for Conservation of Historic and Artistic Works (IIC), the International Council on Monuments and Sites (ICOMOS) and the International Council of Museums-Committee for Conservation (ICOM-CC).

Codes of Ethics, International Charters and Documents have over time set the legal and ethical limits of documentation. The earlier attempt to draw down the principles of conservation was the Sixth International Congress of Architects, which took place in Madrid, 1904. In this oldest international document the intention to preserve any existing documentation and its strong connection with the original can be observed in an immature way. Later, the Athens Charter for the restoration of Historic Monuments, 1931, underlined the need for documentation. In the Venice Charter, 1964, the documentation in the form of critical and analytical reports, illustrated with drawings and photographs, was emphasized. The Burra Charter in 1979, revised in 1999, apart from the already mentioned ideas of documentation, stressed the protection of the records and the fact that they should be publicly available. It was not until the 11th ICOMOS General Congress in Sofia in 1996 that recording came into focus. It explained the reasons and responsibility for recordings, providing details on planning, content, management, dissemination and sharing of records. In particular, and important for the present study, are the recommendations for the Protection of Moveable Cultural Property (1978), where systematic documentation is considered as a measure for the prevention of risks.

2.2.3.2 Methodological issues

Cronyn (2003) emphasizes three major reasons for conservation documentation, focusing on the long term preservation of the artefact, the development of conservation methodology and material-based interpretation. Proper recording and documentation of material evidence in conservation records provide invaluable information for the study and interpretation of the artefact. Conservation records ensure long-term preservation and assist in preventive conservation and re-treatment of the artefact. Caple provides a more detailed analysis stating that recording and documentation '*marks one of the crucial changes from craft to a profession*' (2006, p.6).

According to contemporary museum standards the conservation record should cover the examination, treatment plan, treatment and preventive conservation. As shown in Graph 3 the documentation of examination includes identification information, description of structure and materials, condition and history of the object. The conservation record should describe and justify the treatment proposal, including the potential risks encountered. The treatment documentation consists of the description of techniques or procedures and materials applied, in addition to the nature and the extent of the alterations introduced to the object, along with any necessary additional information. The preventive conservation documentation, usually the last section of conservation records, provides data about health and safety and the overall stability of the object, as well as recommendations for environmental conditions, handling, storage and display of objects.



Graph 3: Information that should be included in conservation records (Graph author's own).

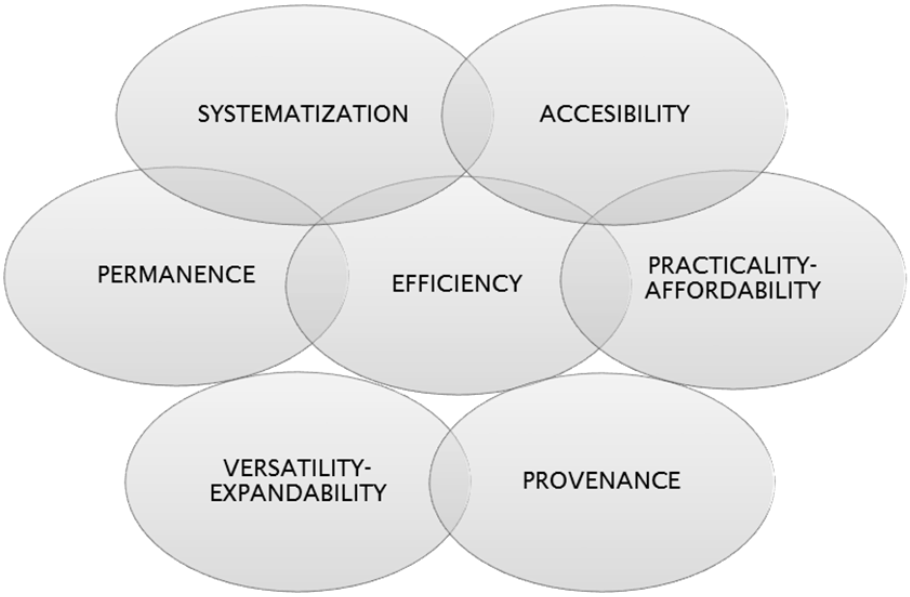
Conservation documentation methodology has to employ different techniques in order to be efficient. Visual records have to be of the appropriate level in order to not only present the material evidence effectively, but also to be

useful for the artefact's interpretation (see section 2.3.3.1 and chapter 3 for a review of visualization methodologies, section 4.3 for further analysis and proposals for development and Chapter 5 for the evaluation of virtual visual analysis) . Moreover, conservation records add to the professional body of knowledge and are useful by the institutions who possess the objects, as well as by other professionals. Their appropriate dissemination is vital and their accessibility is a necessity. Otherwise, records cannot fulfil their goal completely. In order to be efficient and accessible, a certain degree of systematization is needed, which leads to scientific co-operation and advanced dissemination along with better structured, higher quality data (see section 2.3.3.2 for current systematization approaches and 4.4.2 for advanced alternative options available). However, practical aspects of documentation should be taken under consideration, as documentation strategies have to be affordable and time- and cost-effective, in order to be fully incorporated in conservation.

The conservation record is closely related to the various aspects of the object's biography. It forms part of the history of the object, as the conservation event is part of its *museum life* and simultaneously depicts and describes its history, as data regarding its manufacture, use, decay and previous repairs are revealed. The record should reflect its dual nature, without overestimating either the earlier history of the object or its recent one. Provenance of the artefact, as conceived by archaeological terminology as well as provenance of the data, regarding the technological terminology, should be incorporated in the conservation record, which is intended to preserve the metadata of the whole project. In particular, in case of treatment proposals, the versatility of records is highly accredited as a means to test hypotheses and justification. See section 5.3.2.3.3 for a case study of advanced conservation documentation and monitoring in numismatics.

Condition assessment of artefacts is a common practice in museums, which ensures the safeguarding of the material integrity of the artefacts exhibited, loaned or stored. Such actions are dictated by the unstable nature of artefacts, whatever the environmental conditions. Hence, the record has to be expandable, so as to include description of artefacts as inevitable changes and alterations take place. The need for expandability of records is analogous to

the fundamental rule of re-treatability of objects. Another issue of great significance is the permanence of records. Conservators consider the long-term effect of materials used in conservation and seek to employ those materials and techniques with the best properties. Similarly, the record, being part of the artefact, needs to be maintained for future generations. Documentation needs are summarised in Graph 4.



Graph 4: Documentation needs (Graph author's own).

2.2.3.3 Problematic aspects

The strategies employed in museums and cultural heritage organizations do not manage to fully meet the documentation needs discussed above (for an overview of traditional documentation techniques see Appendix A2). Their main disadvantages are summarised as follows:

- They fail to depict the amount of detail needed because they lack accuracy.
- They do not provide data about three-dimensionality. The limited pictorial 2D representation excludes the third dimension, the one most

critical in the understanding of material characteristics and decoration details.

- Their level of objectivity is questionable due to the fact that it depends on the designer's or photographer's judgement.
- There is an obvious lack in a generally approved documentation system.
- Accessibility to conservation archives is restricted.

Another crucial issue for conservation documentation is the misconception of practicality. Cultural organizations usually prefer low-cost, quick and easy to perform documentation strategies which provide minimum level records. The most widely used documentation systems include basic level information for the artefact provenance, its description, condition and treatment, along with digital images inserted in the word file. Questions arise whether a record, which is insufficient, difficult to be retrieved from the museums' archive, and non-accessible for the conservation community, fulfils any use other than the simplest identification of the artefact. These types of recording strategies, although generally considered as practical solutions, are actually time consuming and impractical. Due to their inefficiency, they turn out to be useless because they do not meet the original scope and potential of documentation, which is to provide a comprehensive guide to every aspect of the artefact for future generations.

In the case of large excavation projects, where a tremendous variety and quantity of artefacts are involved, the documentation of treatment and condition may be occasionally omitted, due to pressing deadlines for the completion of the conservation project and the proper archaeological interpretation of artefacts. It is usual for previous operations to be neglected and largely not documented (Dooijes and Nieuwenhuyse, 2009). Undoubtedly, the fragmentarily documented operations provide an insufficient description of the collections' museum life. It constrains the progress of the conservation profession as a whole, especially in the case of conservation methodological treatment and aging research. The lack of information creates a knowledge gap and a communication problem for the conservator and the object. Condition assessment becomes more problematic, and the overall judgement of alterations, including patina, restoration, deterioration, damage, and characterization of deterioration phenomena is complicated. Conservators will

be worried about the absence of information concerning the object's overall resistance and its weak points.

Of course, the materials and the procedures used in previous operations are important factors to consider when designing new ones, because of compatibility and reversibility issues. Previous repairs, neither documented nor based on sound scientific knowledge, are witnesses of the skills of past conservators, who worked without the technological means of modern conservators (Skinner, 2009). The study of old repairs can be seen as recognition of their contribution to the protection of cultural heritage. Moreover, these records reflect not only skills and technological means, but also attitudes and ideas towards the collections. In that way, recording strategies reflect the society during which these were created (Caple, 2006).

The use of 3d documentation provides enhanced visualization compared to 2d representations (section 2.3.3) and offers the possibility for advanced illustrations (section 2.3.3.1). The systematization approaches currently available are presented in section 2.3.3.2.

2.2.3.4 Digital preservation

The preservation of documentation and conservation records is an obligation for conservation according to relevant codes of ethics. The longevity of materials and methods used for the production and use of records is a necessity, which cannot be fulfilled via digital means solely (AIC, 1994). As a result the accepted strategies employ both physical and electronic media. The Andrew W. Mellon Foundation organised a meeting in New York in 2006, where the shift from print to digital forms of documentation, as well as management and dissemination, were discussed. The digitization of conservation records found a wide acceptance and was characterised as desirable, especially in the case of degrading forms of documentation, such as photographs and radiographs. However, paper documentation is considered a necessity, which cannot be overlooked by any digital strategy (Rudenstine and Whalen, 2006).

Traditional means of documentation are subject to material degradation. For example, transparencies, largely used for pictorial documentation, gradually deteriorate over time leading to inaccurate colour representation (Martinez *et*

al., 2002). Photographs are also subject to deterioration under incorrect environmental conditions (Lavédrine, 2009). Paper and archival material are vulnerable due to decomposition of organic matter and biological attack (Ogden, 1999). Hence, the longevity of textual and pictorial data on conservation reports is negatively influenced by the inevitable process of material degradation. Actions of environmental control can postpone the life span but it is well known that degradation cannot be totally reversed. As a result traditional museum archives cannot assure the preservation of knowledge for future generations.

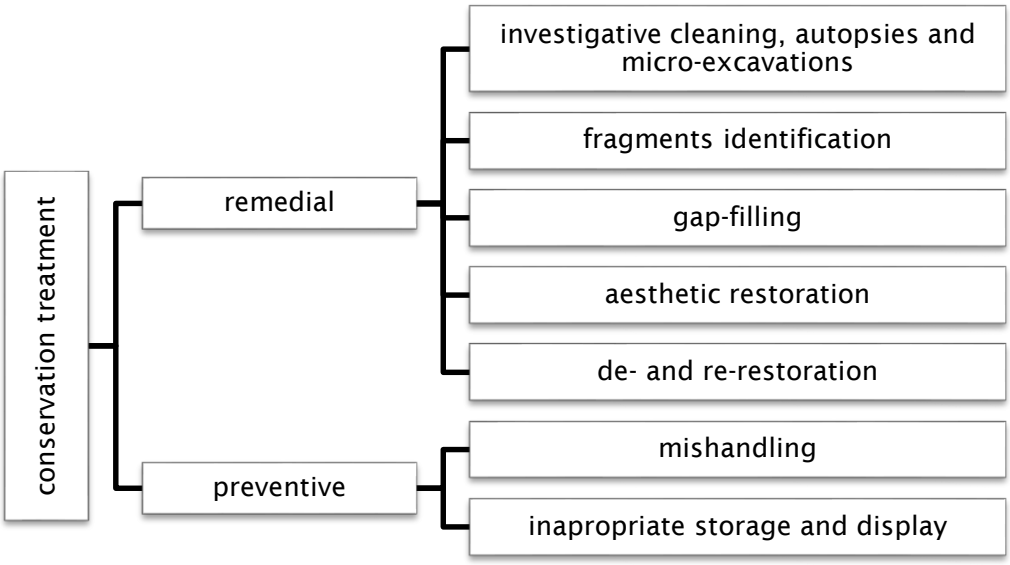
Similarly, the long-term preservation of digital documentation is problematic too (Corrado and Moulaison, 2014). This has been considered as the main disadvantage of digital imaging for conservation reports because issues of digital records preservation and maintenance remain unresolved. The digital media today cannot secure data preservation for more than a few years, while conservation records need to be maintained for at least two treatment generations from now, approximately 100 years. The main aspects of data permanence are data formatting and storage medium (Staimer, 2012).

A conservation record is a selection of textual, pictorial and numerical data in different formats, including word files, pdfs, digital images, drawings and graphs. Access to these datasets is dictated by the combination of hardware and software, and the mediation of technology and data, which provides safety to data preservation as long as the technology and data interact. Preserving the files is a difficult but feasible task, but preserving the same technology, the digital process so as to access the file, is impossible due to the rapid development of the IT industry. Processes, such as migration and emulation[9] commonly used by archivists, have limitations regarding their sustainability, accessibility and practicality (Heslop *et al*., 2002). The storage media used are not appropriate for long term preservation because of the permanence of the data on the medium, the medium's susceptibility to environmental factors and its resilience or immutability (Staimer, 2012).

[9] Migration means moving data to a different format, change in media internal structure, from one version of an application to a later version, or from one application to another. Emulation means the use of one system to reproduce the functions and results of another system (Pearce-Moses, 2005).

Useful recommendations for widely accepted format such as TIFF (Tagged Image File Format), production of stable hardcopies, archiving on an external hard drive, and well-organized digital archives are followed by cultural heritage organizations (Kushel, 2002). These recommendations are good starting points, but cannot be used as a panacea. There are aspects of digital conservation documentation, such as 3D digitised virtual artefacts that cannot be reproduced in a hardcopy format. If they do, they present neither their original functionality nor their characteristic advantages of interactivity, communication-presentation-dissemination quality and versatility-expandability. A solution to the problem of digital permanence is the standardization of records, management policies and procedures. However, digital applications in conservation, especially those in 3D, are still in an early phase of development. They can be better conceived as experimentations rather than common practices in conservation methodology.

The problems already discussed, and dilemmas regarding preventive and remedial conservation and conservation documentation, are summarised in Graph 5.



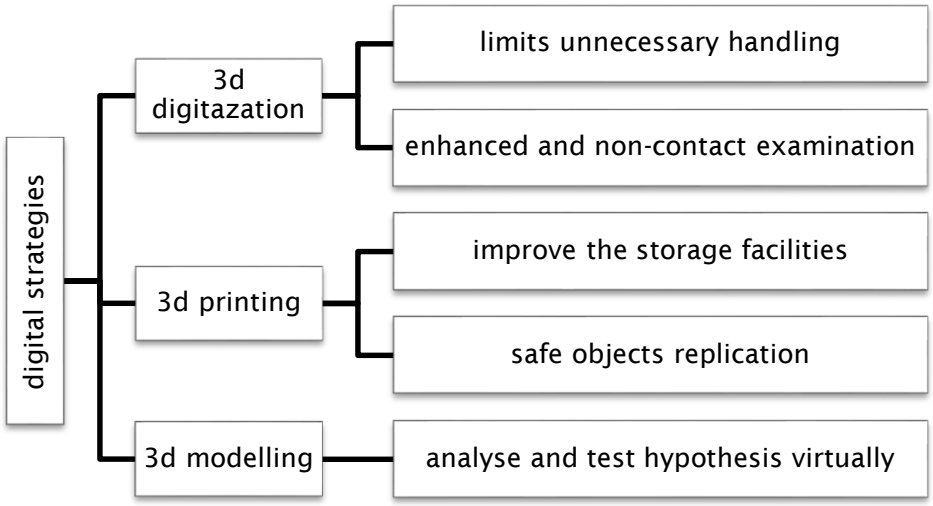
Graph 5: Problems and dilemmas attributed to preventive and remedial treatment (Graph author's own).

2.3 Digital solutions

This section relates the problematic issues presented above to available technologies so as to define the level of interference of digital techniques in solving conservation problems.

2.3.1 Informational preservation

3D digitization limits unnecessary handling, improving the preservation of the original artefacts. Computational tools provide options for enhanced and non-contact interaction with the archaeological materials. Furthermore, 3d digitization, modelling and 3d printing can improve the storage facilities through the production of appropriate storage cases. Replication via 3d printing can be used as an alternative to moulding and casting. Consequently, digital technology provides an alternative methodology able to deal efficiently with preventive conservation problems discussed in section 2.2.1. The role of digital technology is considered as a preventive conservation measure, which, in addition to other strategies employed in museums, such as environmental monitoring, ensures the preservation of material culture (Graph 6).



Graph 6: Digital strategies in the service of preventive conservation (Graph author's own).

Imaging and digitization techniques are discussed in chapter 3. Proposals for developments to meet conservation objectives are presented in chapter 4, and the evaluation of imaging techniques on selected material, in a fragmentary state which requires advanced preventive conservation care, is presented in chapter 5.

2.3.2 Digital technologies in remedial conservation

Computational tools assist also in the execution of remedial conservation operations via the use of advanced digital capture techniques, virtual reconstruction and 3d printing. As discussed in section 2.2.2 the execution of such operations following the conventional methodology is in many cases problematic. In the following section the most useful techniques based on current practice will be discussed.

2.3.2.1 3d tomography

In general digital capture techniques enhance the examination of artefacts and minimise manual execution of operations. In regard to examination and visual analysis, digital capture techniques bring to light features of the artefacts that may have been underestimated or not considered by conventional means of examination (see Chapter 3 for an overview of digital capture techniques). Hence, advanced computational tools enable better understanding of artefacts, and by extension a more meaningful interaction with them.

3d tomography overcomes the limitations of manual conservation and provides an alternative to cleaning operations in traditional investigations, micro-excavations and archaeological autopsies (Stelzner *et al.*, 2010, Re *et al.*, 2015) (Figure 17). A detailed discussion and literature review about the use of 3d tomography is located in section 3.4.1.

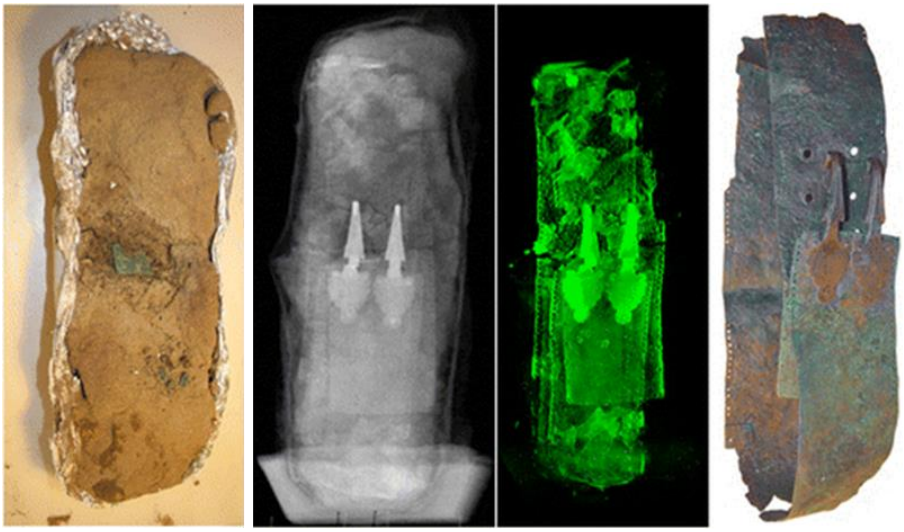


Figure 17: X-ray imaging of a soil block from an archaeological excavation and the extracted metal belt. The block of soil, radiograph, 3d volume rendering and the object after conservation. Graphical abstract. Available from: http://link.springer.com/article/10.1186/s40494-015-0033-6 (Re *et al.*, 2015).

The advantages of digital micro excavations via tomographic techniques are summarised as follows:

- Digital micro-excavations enable improved preservation of archaeological material, avoiding actions which may threaten their material integrity, so it is considered to be a preventive conservation measure. The conservator and curator may choose not to execute the physical autopsy if the data revealed from 3D scanning show that the materials hidden inside are in a poor conservation state and cannot withstand physical manipulation.
- Digital micro-excavations enable evidence-based conservation decision making, avoiding judgements based on general knowledge. For example the possible presence of valuable and sensitive material inside funerary pots is based on general knowledge about burial customs. The actual presence of valuable and fragile archaeological artefacts inside the pot, revealed from digital micro-excavation, is an evidence-based conclusion. Adequate actions can then be undertaken in light of the findings.

- Digital micro-excavations are cost-effective. Conservators are able to choose not to devote the amount of time and skills in cases where digital micro excavation revealed the absence of valuable contents inside blocks of soil and pots.

A critical discussion of advantages and limitations of 3d tomography compared to other digital capture techniques can be found in section 4.3.1.

2.3.2.2 Digital restoration

The contribution of virtual reconstruction in remedial conservation tools is primarily the virtual execution of impractical or ethically forbidden conservation treatments and assisting in decision-making and conservation dilemmas through visualization. Operations can be applied virtually in 3D models and the results can aid decision making and enrich or justify treatment proposals. Conservation hypotheses can be tested virtually, avoiding the handling required for traditional approaches. Digitization and virtual reconstruction/restoration of artefacts for conservation purposes is proposed in various cases, such as those involving extreme dimensions and weight, or fragile, unstable, complex artefacts, whose restoration presents technological problems or raises ethical issues (Figure 18).

The role of digital technology in solving conservation problems has been discussed in the literature, although this field of research remains largely unexploited. The earliest operations are those of simple processing of images of paintings, crack removal, virtual cleaning and virtually joining portions of paintings. The data provides valuable information for the conservator and curator for assessing the options for real treatments (Barni *et al.*, 2005) (Figure 209). More recently, rapid technological developments enable a more effective use of digitization technologies and 3D graphic modelling in conservation. In the case of the Pietranico Madonna (Figure 200), the advanced application of virtual reconstruction assisted in the examination and reassembly of the broken pieces, as well as appreciation of the polychrome decoration (Arbace *et al.*, 2012). Interestingly enough this approach is not a novelty in conservation. It has been used in Italy since the 1970s (Huber *et al.*, 2009; Melillo, 2013), but the use of 3d technology signals a significant improvement in the methodology in terms of treatment planning, risk assessment and accuracy.

Figure 18: Togatus statue of Caligula, Virginia Museum of Fine Arts (left) and 3D restoration model. The Digital Sculpture Project. Virtual World Heritage Laboratory. Available from: http://www.digitalsculpture.org/papers/abbe/abbe_paper.html

Figure 19: Virtual Restoration with Image Inpainting Techniques, example from the Theran wall paintings. Computer Vision, Speech Communication & Signal Processing Group. National Technical University of Athens. Available from: http://cvsp.cs.ntua.gr/research/thera/

Figure 20: The Pietranico Madonna, initial status after the earthquake (left), digital restoration (right). (Arbace *et al.,* 2012, pp. 335, 338).

Also, laser scanning and reproduction technologies assisted in paintings conservation, in a demanding project of restoring the bio-deteriorated wooden support of a badly damaged 400-year-old crucifixion painting, part of a wooden epitaph from a church at Rothenstein in Germany (Ioannides and Wehr, 2002). Another example is the Lichfield Angel; a fragmented carved limestone panel with painted decoration, which was recorded and represented in exceptionally fine detail. Textual and graphical annotations of high resolution three-dimensional scan models were used for the documentation. Conservation professionals can access and interpret information about the condition, materials and technique of its manufacture. This project enhanced people's understanding of the function of the sculpture within the lost monument and provided a reconstruction of its original appearance (Geary and Howe, 2009) (Figure 21).

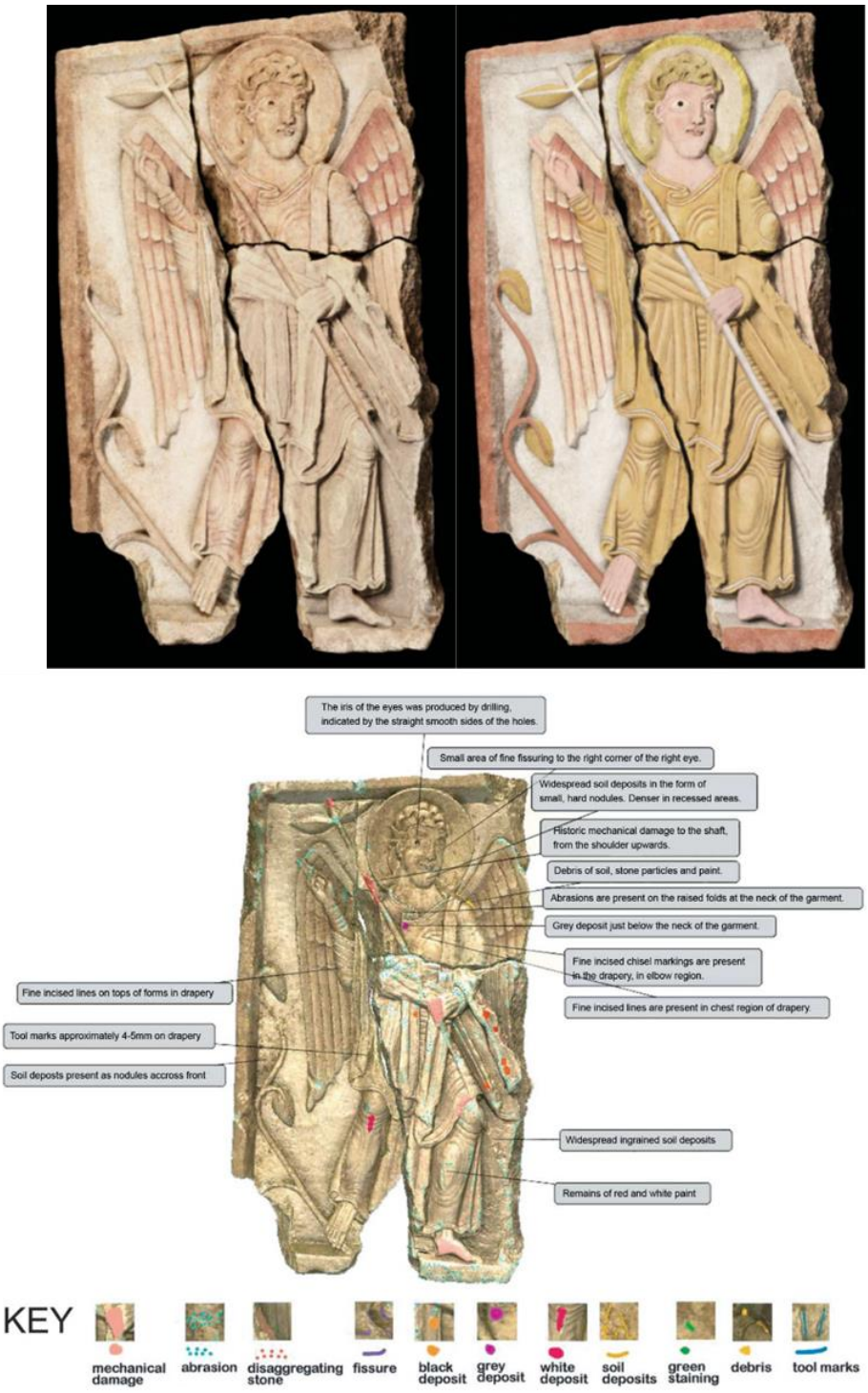


Figure 21: 3D model of the Lichfield Angel, a fragmented carved limestone panel with painted decoration virtually cleaned (top left) and restored (top right) and graphically and textually annotated with condition information (below) used for documentation and interpretation of condition, materials and techniques of its manufacture (Geary and Howe, 2009, pp.174, 172).

Also, 3d modelling enables the simulation and testing of the function of objects, providing views of artefacts difficult to approach using traditional means, such as the virtual reconstruction of four ancient clocks from different Italian regions (Pennestrì *et al.*, 2006). Three dimensional computer graphics can introduce ancient scientific instruments with great historical and cultural interest, like the Schickard calculator, to the public. These applications provide interactivity, as a visitor may perform calculations with it and watch its gearwheels move as Schickard did (Hanisch *et al.*, 2000). The most reknowned example is the virtual restoration of the Antikethyra Mechanism (Figure 22).

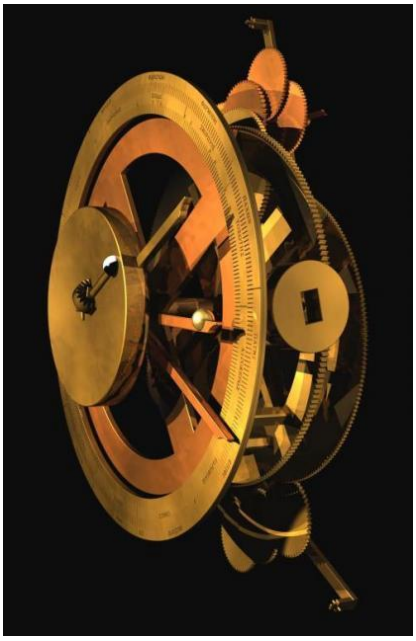


Figure 22: The Antikythera mechanism. Virtual reconstruction of the front gears and dials. The Antikythera Mechanism Research Project. Available from: http://www.antikythera-mechanism.gr/node/202

Worth mentioning is the application of virtual reconstruction in de- and re-restoration dilemmas, where conservators face practical and ethical dilemmas: aesthetics and/versus authenticity and/versus preservation (see section 2.2.2.5 for a discussion on de- and re-restoration problems). The treatment can be focused on the long-term preservation of cultural heritage, following preventive conservation environmental measures, while the original appearance of the artefact can be appreciated in its digital version, with

respect to authenticity. This approach is in accordance with ethics and contemporary conservation theory, because it encourages the preservation of the original material, and simultaneously the presentation of its authentic appearance without neglecting the history of the object, expressed via its previous restoration. Moreover, any risks encountered in complex remedial treatment are avoided. Consequently, virtual reconstruction safeguards both material and aesthetic integrity, while simultaneously enhancing investigation and enabling better preservation. For example, the surface layer of a Renaissance painted *cassoni* damaged by over-cleaning would require extensive reconstruction, an action considered unacceptable according to codes of ethics. Digital reconstruction provided a view of the object in a more authentic state, closer to the original intention of the artist (Kerr, 2008).

Application of digital techniques in conservation practice is in accordance with the principles of conservation, and enables the protection of physical artefacts in a way superior to traditional approaches. Giusti (1999), in a discussion of the reversibility of restoration of stone artefacts, referred to the actions of replication, and although she expressed her scepticism about the removing of the original statues from their setting, she concluded that protecting the fragile works of art from the agents of deterioration and preserving them, until more environmentally and technologically advanced future conservators took action, is a strategy that respects the principle of reversibility. Nowadays, replication can be achieved more reliably than in the past by means of 3d printing, so as to protect the physical artefact for future generations of conservators. Moreover, virtual conservation enables the testing of restoration hypotheses, the experimentation with different restoration scenarios. Digital capture techniques provide tools for revelation operations to be executed virtually, and investigation and research activities to be conducted non-destructively. Considering the above, although reversibility is still not completely achieved, just like Smith had predicted (1999), there is no doubt that contemporary conservators can be closer to this ideal state than previous generations.

Digital restoration case studies are presented in section 5.4.2.4 and in Chapter 6.

2.3.2.3 Digital refitting

The development of working methodologies for digital refitting of fragments is of fundamental importance for archaeological research, and it is considered as one of the most valuable contributions of archaeological computing in conservation practice (see section 2.2.2.2 for a discussion of fragments matching problems). Computer-aided reconstruction of archaeological objects is a complex signal processing problem, which cannot be compared to any other type of jigsaw puzzle. The latter has been discussed in the literature from the 1960s, but these approaches do not provide a solution to the problem of archaeological fragments matching, although it can help as a starting point for future developments. The main problem is that the nature of archaeological material, with its particular characteristics, is unique. The core differences are briefly summarised in the following list:

- The original shape, referred to as frame, and decoration of the object is not known
- The fragments found do not necessarily correspond with a complete artefact. Some fragments may have been lost and the presence of gaps of various sizes is common
- Even well preserved material has signs of deterioration, which are not uniform in the surface of the object. Some fragments may have been deteriorated more than others, even if they are neighbouring pieces of the same object
- The complex three-dimensionality may result to wired matches, such as overlapping of fragments.

The categorization of matching techniques in two groups is proposed: '*apictorial*' (shape based, contours matching), and '*pictorial*' (colour and texture based approaches). The latter analyses the visual content of the fragments, using either solely texture based approaches or a combination of texture and shape data (Kleber and Sablatnig, 2009). Another classification usually discussed is the 2D and/or 3D reconstruction problem.

An approach to puzzle solving focuses on fracture junction, usually T or Y shaped, meaning the points where three fragments join and form a correct

match (Goldberg *et al.*, 2002). The general reconstruction scenario, proposed by Huang (2006), is a repetition of a four step process: data segmentation, feature selection, pairwise matching and multi-piece matching. Sagiroglou and Erçil (2006) presented a surface texture and picture approach for 2D reconstruction, by expanding the boundary of each piece using in painting and texture synthesis methods, and maximizing the correlation based on matching feature values obtained from these predicted regions. Huang (2006) presented a method for automatic reassembly of fractured 3D solids based on geometric information of fracture surfaces of the fragments. The methodologies proposed are based on different aspects of the data, ranging from surface markings to surface intrinsic characteristics (Cohen *et al.*, 2010).

The condition of archaeological material does not allow curve matching, following classical approaches. Elastic curve matching is an alternative method, able to deal with weathered fragments, as it detects each point correspondence between a pair of fragments boundaries (Willis and Cooper, 2008). Another method proposed for eroded surfaces is segmentation based on the Cone Curvature feature, which yields a flexible measure of curvature in solids (Adán *et al.*, 2012). Additional knowledge of typology has been used for classification of fragments (Gilboa *et al.*, 2004), while other approaches are based on volumetric models (Kampel and Sablatnig, 2003).

Willis and Cooper (2008), on their review of computational reconstruction, referred to systems for 3D reconstruction of pottery, based on measurements of their outer surfaces, outer fracture curves, and their junctions. They consider this Bayesian method as the most efficient, because they make use of the entire fragment outer surface and are able to solve multiple puzzles simultaneously (Willis and Cooper, 2008).

Considering the computational cost of processing, multi-scale approaches have been developed. Initially, incorrect matches are identified by coarse fragments fracture representation, and then the processing is repeated with limited fragments at higher detail (Willis and Cooper, 2008). In an experiment with 5 broken ceramic tiles, with a total of 112 fragments, the algorithm, based on the shapes of their outlines, started with 166.626 initial pairs, and returned 277 pairs, of which 46 were true (da Gama Leitao and Stolfi, 2002).

The reconstruction of the Theran wall paintings attracted the attention of computer scientists, who have proposed different computer-aided reconstruction methodologies. The Theran wall painting fragments form an explicit dataset for experimentation, due to the quantity and quality of fragments, as well as the archaeological significance and the well-structured research on the site, from its discovery until the present days.

An approach to the problem of reconstruction was tested on two groups of fragments of 262 and 936 pieces. The fragments are photographed and the contour is obtained, in an attempt to extract the maximum possible information from their contour shape. The fragment of the greater number of contour pixels ("reference") has a fixed position, while the others (rotating fragments) are rotating in order to find the orientation of the contour that form an "island" of matching fragments (Figure 23). The resulting "artificial" fragment can be visually inspected using image processing tools. Gaps between fragments and alteration due to decay and damage of fragments were computed so as to minimise the incorrect matching. The final results reported 60% correct matching versus 40% accidental matching (Papaodysseus *et al.*, 2002). The weakest point of this methodology is that colour continuation, subject and thematic continuity, three dimensional features and texture were not taken under consideration.

Figure 23: An "island" of matching fragments from the Theran wall paintings (Papaodysseus *et al.*, 2002, p. 1285).

The thematic content of the Theran drawings was encountered in a couple of alternative methodologies proposed by Rousopoulos (2011), focused on fragments of the third floor of the house called 'Xeste 3', mainly decorated with black and blue stripes. The first approach, based on the artist's intention to draw parallel lines/stripes, resulted in the reconstruction of more than 25 pairs of fragments. However, the authors state that the reconstruction of any drawing with repeated patterns can be benefited by this approach, even in case of gaps. Based on the fact that the design follows a parallel-lines pattern with various widths due to the inaccuracy of the manual painting, this approach estimates whether a set of fragments derive from the same wall painting. The second methodology uses a set of geometric prototypes, spiral, hyperbolae and ellipses, produced by guides/stencils, in order to reconstruct wall paintings with missing fragments. It was successfully applied to the "gathering of crocus" wall-painting, and on fragments from the internal walls of the uppermost floor of Xeste 3. If the design pattern of fragments falls within the geometric stencils proposed, the fragments are positioned correctly, so as to fit the same schema (Rousopoulos *et al.*, 2011) (Figure 24). Brown, focusing on a 3-D shape-matching algorithm method rather than contours and thematic content mentioned above, tested the efficacy of repeated ICP alignments in comparison to the ribbon matcher. The latter methodology proved not only more efficient, but also much faster (Brown *et al.*, 2008) (Figure 25). The analysis and simulation of fracture patterns appears to be a promising direction for future research in the computer-aided reconstruction of wall paintings (Shin *et al.*, 2012).

Figure 24: Placement of the wrist fragment using design patterns (Rousopoulos *et al.*, 2011)

Figure 25: Matches found on a spiral (left) and a white (right) data set, using a flatbed scanner to capture high-resolution images and normals and 3-D scanners to acquire geometry (Brown *et al.*, 2008, p. 89).

Archaeological artefacts reconstruction is focused largely on pottery reconstruction (Kampel and Sablatnig, 2004; Marie and Qasrawi, 2005). Other material types included in virtual reconstruction tests are architectural stone fragments (Milojevic *et al.*, 2005; Velios and Harrison, 2007) and wall paintings (Brown *et al.*, 2008; Papaodysseus *et al.*, 2002; Rousopoulos *et al.*, 2011). Another area worth considering is the work of forensic science in documents reconstruction (Butler *et al.*, 2012; De Smet, 2008). Other material types have been explored at a lesser extent, even if the potential benefit from automatic reassembly is significant. For example, the demanding issue of glass reconstruction has been disregarded. Archaeological and historical glass is extremely fragile and has a much higher chance of fracture than other material types. Even if the quantity of excavated glass cannot be compared to pottery, its reconstruction is much more demanding, because of the fragility of the material and the stricter rules applied in handling. A possible explanation is the problems encountered in digital capture of glass, because of its reflectivity and translucency.

A semiautomatic digital refitting case study is presented in section 6.2.

2.3.2.4 3d search and analysis

The development of methods for 3D search and analysis are of particular importance for classification, but also for conservation and artefact studies, considering their efficiency in non-contact retrieval of information regarding

technological, morphological-morphometric and volumetric analysis as well as digital refitting.

A sufficient amount of work has been done in the field of facial reconstruction, based on either facial anatomy, or the average soft-tissue measurements, or the combination of both. The later methodology helped scientists obtain the physiognomy of a well-preserved, completely wrapped mummy, based on three-dimensional CT data (Cesarani *et al*., 2004). Other examples in the literature are the reconstruction of the face of Dante Alighieri, the application of geometric and morphometric analysis in the case of Angelo Poliziano (Benazzi *et al*., 2009), and the virtual reconstruction of faces of Byzantine icons (Lanitis *et al*., 2012). The virtual reconstruction of fossil skulls, since its emergence in 1995, has received attention too (Fantini *et al*., 2008).

The analysis of 3D models can assist conservation studies and lead to conclusions about materials degradation. In the cases of very fragile objects, scanning and digitization can be completed shortly after their recovery. This enables documentation of the object before the start of conservation operations, which can affect the appearance of the object, introducing changes due to shrinking, chemical treatment or mechanical strain. The virtual model of the artefact can be used for 3d mapping and for a metrical evaluation of different layers, and for the determination of volume, volumetric weight and manmade traces (Hanke *et al*., 2008) (Figure 26).

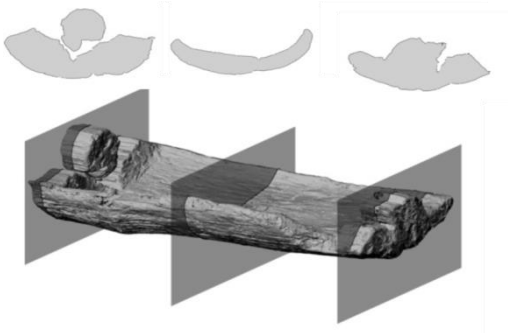


Figure 26: 3D model of the wooden trough with three sections showing the detached core of the log and traces of fissuring and deformation (Hanke *et al*., 2008, p.189).

Of extreme significance is the ability to analyse 3d shapes, and perform searches based on similarity of 3d shape and surface, in order to quantitatively measure complete artefacts or parts of them (Funkhouser *et al*., 2003). There is no doubt that the complexity and variability of cultural heritage artefacts is a challenging task for 3D-shaped analysis algorithms, while at the same time the potential of successful application can greatly enhance current conservation practices. A necessary step in the retrieval process is the transformation of data, and the extraction of descriptors so as to characterize features of 3D objects, which can be categorised in three groups based on their form: the feature vectors, histogram statistics and structural graphs. Characteristic examples or relevant applications are the study of stone tool technology (Abel *et al*., 2011), ceramics and bone (Drenth and Mom, 2009; Rowe *et al*., 2003).

2.3.2.5 3D printing

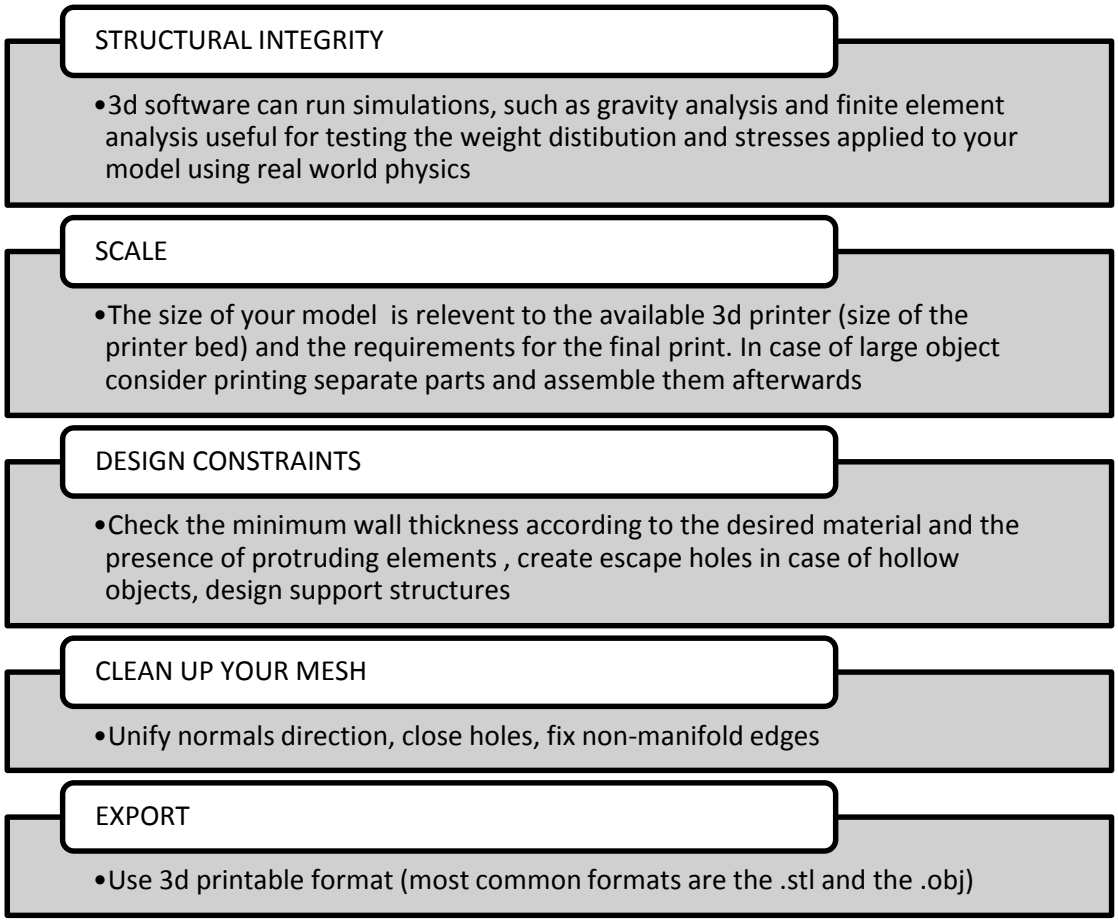
Apart from visualization, digital restoration and refitting, 3d technology offers opportunities for fabrication of physical objects directly from CAD data sources via rapid prototyping or 3d printing. Computer Numerically Controlled (CNC) processes are based on the removal of material in order to achieve the final shape, while 3d printing methods add material layer after layer (Kamrani and Nasr, 2005). The greatest advantage of 3d printers is that they are able to realize design and accuracy with more versatility than any other mode of production, human or machine.

2.3.2.5.1 Methodology

The whole process can be divided into three steps; the 3d modelling, the 3d printing and the post processing.

2.3.2.5.1.1 3d modelling: Designing models for 3d printing

The preparation of your model for 3d printings includes the testing of structural integrity and size of the model according to the requirements for the final print, taking under consideration the design constraints according to the chosen material and 3d printing method. Before exporting the model to a 3d printable format it is necessary to check your geometry so as to avoid open meshes (Vaughan, 2012) (Graph 7).



Graph 7: 3d models design recommendations for 3d printing (Graph author's own).

2.3.2.5.1.2 Instrumentation

There are two main types, the selective deposition printers and the selective binding printers. The former deposit layers of raw materials while the later binds raw materials using heat or light to solidify power or a light sensitive polymer (Lipson and Kurman, 2013). 3d printing technologies such as stereolithography, selective laser sintering, inkjet powder printing, and laminated object manufacturing use binding processes, while fused deposition modelling and polyjet use deposition processes. The most common technologies are the stereolithography, the selective laser sintering and the fused deposition modelling (Warnier *et al.*, 2014)

In stereolithography (SLA) the raw material, fluid resin, is hardened by UV or laser (photopolymerisation). It was developed during the 80's and the first commercial desktop-class SLA 3d printer appeared in 2012. The advantages are the surface quality and accuracy (Figure 27).

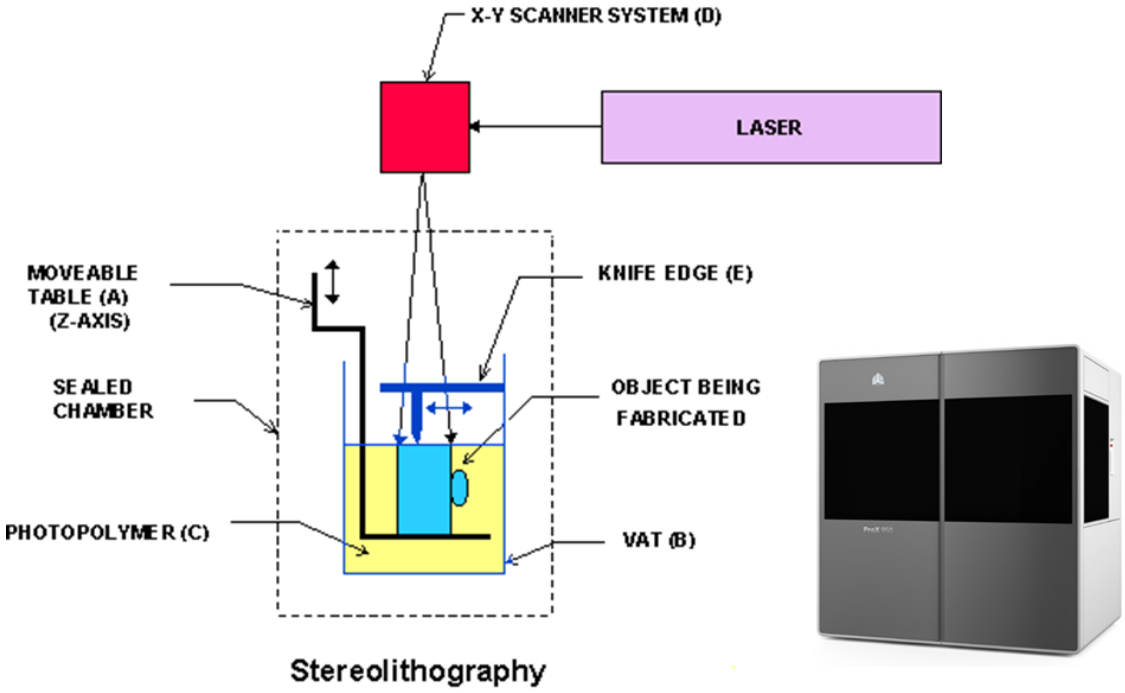


Figure 27: Schematic representation of SLA. A moveable table (A), is placed initially at a position just below the surface of a vat (B) filled with liquid photopolymer resin (C). As the laser beam is moved in the X-Y directions guided by information from the CAD the resin solidifies (left). Available from: http://www.additive3d.com/sl.htm and the Professional SLA 3d printer ProX TM 950 (right). Available from: http://www.3dsystems.com/

Selective Laser Sintering (SLS) powders are bound together and form solid objects using a high powered laser. SLS has found applications in industry and creates durable, uniform quality objects. Nevertheless, it is not as detailed as other techniques. Available materials are metal, plastic, elastomers, ceramic, or glass (Kruth *et al.*, 2003). SLS was developed during the 80's and commercialized at the early 90's. 3d Systems and EOS are large manufacturers of SLS 3d printers. It is expected that more accessible instruments will be

available soon, because of the expiration of the patent (Warnier *et al.*, 2014) (Figure 28-29).

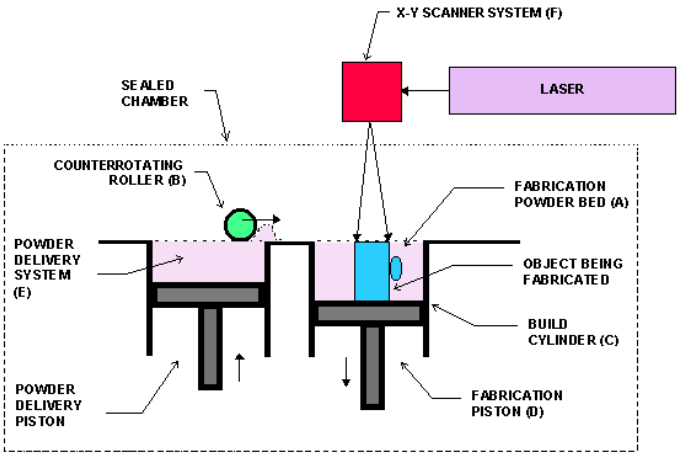


Figure 28: Schematic representation of SLS. A laser beam is traced over the surface of a powder (A), spread by a roller (B) over the surface of a build cylinder (C). (up) Available from: http://www.additive3d.com/sls.htm

Figure 29: SLS 3D printer sPro™ 230. Available from: http://www.3dsystems.com

Sheets of raw materials, usually plastic or paper and less commonly metal, are fused or laminated using heat and pressure. Then cut into the desired shape by a computer-controlled laser or knife. The strongest advantages of this technology are the low cost, the speed of manufacture, the well-known and readily available materials and the absence of size restrictions. Nevertheless, LOM is not popular because of lack in accuracy compared to other 3d printing

methods. Helisys of Torrance, California, USA (now Cubic technologies) who invented LOM continues to further develop the method, by providing new materials such as metals and post-processing methods (Figure 30).

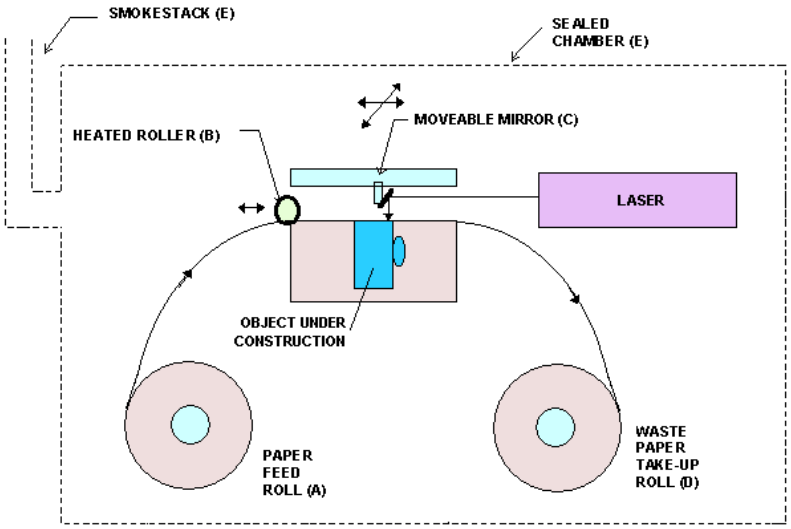


Figure 30: Schematic representation of LOM. The paper is unwound from a feed roll (A) onto the stack and bonded to the previous layer using a heated roller (B). The profiles are traced by an optics system that is mounted to an X-Y stage (C). After cutting the geometric features of a layer is completed, the excess paper is cut away (top) Available from: http://www.additive3d.com/lom.htm. Laminated Object Manufacturing Machine. Helisys LOM 1015 (below).

One of the most common and the cheapest 3D printing methods is the fused deposition modelling (FDM). The raw material is a spool of thermoplastic wire, which is melted and placed by the printer's nozzle. The use of thermoplastics lead to fabricated objects with mechanical strength but usually post processing is necessary so as to avoid the layering on the surface. It was developed in the 80's and commercialised by Stratasys (Figures 31).

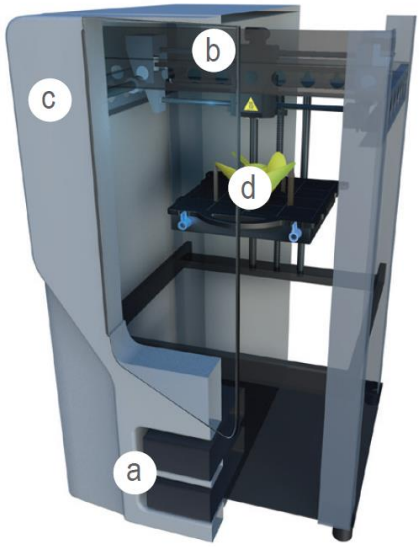


Figure 31: FDM 3D printing. Material cartridges (a) supply plastic filament to the extrusion head (b). In the heated chamber (c), the head moves in the X- and Y-axes while liquefying and depositing material. The Z stage platform (d) moves down to give the part the third dimension. Available from: http://www.stratasys.com

Of particular importance for the quality of the 3d printed object are not only the materials and instrumentation but also the layer resolution and print time. A thick layer resolution results in a decrease in print time, while fine layer resolution is more time consuming and creates a better surface quality. The speed settings on the printer are also crucial for the quality and surface finish

of print. For example, according to Evans (2012), the Ultimaker 3d printer[10] with a resolution of 0.03mm at a speed rate of 300mm/s can create high quality prints.

2.3.2.5.1.3 Materials

The most common printing material used is plastic, either thermosetting or thermoplastic[11]. The former category is used by SLA 3d printers while the latter is used by laser sintering. ABS thermoplastic models provide the best dimensional accuracy, usually using the FDM technology. Another option for 3d printing is the elastomers[12], which provide the manufactured object with a degree of flexibility. Models in polyamide, made from a granular powder, with a granular look and slightly porous surface, fall in this category. They are constructed by the SLS process. Although polyamide allows for complex design and does not have the limitations of other materials it absorbs moisture. Hence, special treatment of the model is required for its use in restoration. Also, models can be printed in transparent resin using the SLA technology (Figure 32).

Figure 32: Comparison of commonly used 3d printing plastic materials (Tinkercad, 2015)

[10] The Ultimaker 2 3d printer is capable of printing up to a .02mm resolution and is considered the fastest, highest resolution FDM (fused-deposition modeling) printer on the market today. It costs $2,499.00.

[11] Thermosetting plastics refer to a range of polymer materials that cure to a stronger form. Thermoplastics are polymer materials that can be repeatedly softened through heating and hardened again by cooling.

[12] Elastomers have the ability to undergo deformation under the influence of a force and regain their original shape once the force has been removed.

Gold and silver objects can be 3d printed using the wax 3D printing and lost wax casting[13] technology (Figure 33). The gold material is a 14k solid gold mixed with copper alloy available in different colours; a very bright yellow gold, a deeper gold with a reddish rose tinge and a white gold. For silver, the material is a solid Sterling silver, made of 92.5% pure silver and 7.5% of copper. Small decorative models like coins, medals and statues can be printed either with the wax 3d printing method or in bronze powder, although bronze printing is still under research (Figures 34-35). During the additive manufacture of the model each layer is dried and the model is cured in an oven. The model can be printed in raw or polished in bronze. The 3d printed bronze objects follow different corrosion rates than the manual-crafted bronze objects (Imaterialise, 2013). Other available metal 3d printing materials are the stainless steel and titanium. The latter is one of the strongest 3d printing materials available and it of offers advanced possibilities for printing detailed models with a minimum wall thickness of 0,2mm (Figure 36).

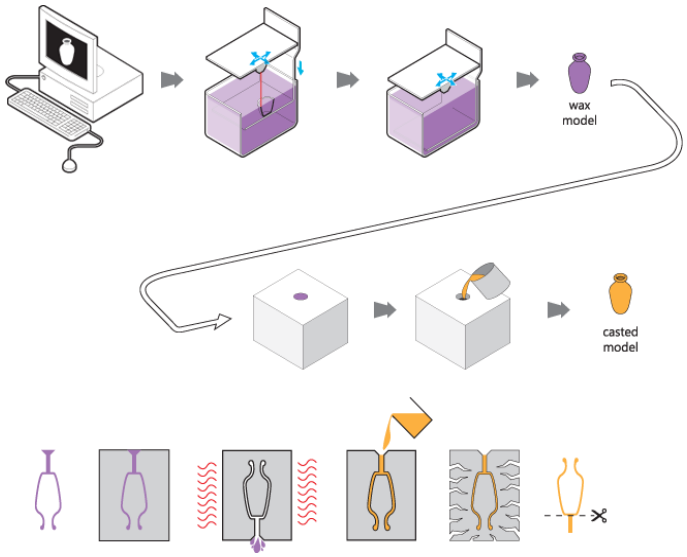


Figure 33: Wax 3D printing and lost wax casting methodology, schematic representation of the 3D printing process. A 3d printing material which is similar to wax is used. Then a casted model is built (Imaterialise, 2014a)

[13] This idea is well known in archaeology as the lost wax technique had been applied since antiquity.

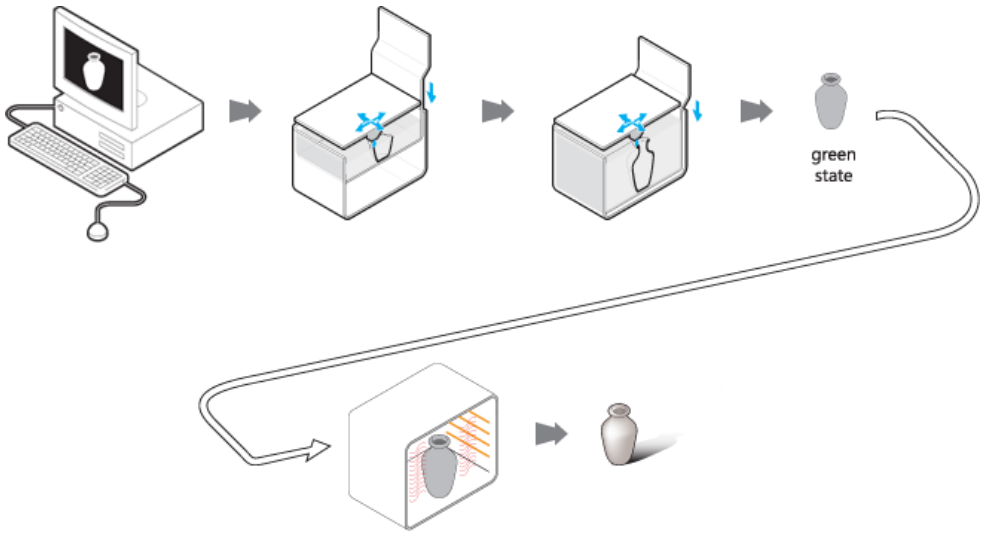


Figure 34: Bronze 3D printing methodology, schematic representation of the 3D printing process. The model is built in layers (green state) and then it is cured in an oven (Imaterialise, 2014b)

Figure 35: 3d printed coin in gold plated brass material. Available from: http://www.shapeways.com

Figure 36: Comparison of commonly used 3d printing metal materials (Tinkercad, 2015)

Ceramic printed models are made from an alumina-silica powder with a porcelain and silica finish and glazing. After printing the model inside its powder bed it is dried in an oven, a process that increases its strength. Then, the model is cleaned from excess powder, fired again and pre-glazed. The final step is again a firing-glazing process, which is a second coating (Figures 37-38). The firing may result in shrinking, cracking and wrapping and is considered as a difficult step in the 3d printing process. Different recipes for ceramic materials have been tested so as to achieve durable objects using firing temperatures up to 1,260 degrees Celsius. At least two firing stages took place. The printed material is porous and glazing can be applied to the surface. Also, another firing is proposed for decorations (Hoskins, 2012; Pugh and Balistreri, 2014). The ceramic prints were used for casting too. Researchers are exploring the possibilities of replicating Egyptian Faience techniques using 3d printing and one firing stage (Hoskins and Huson, 2013).

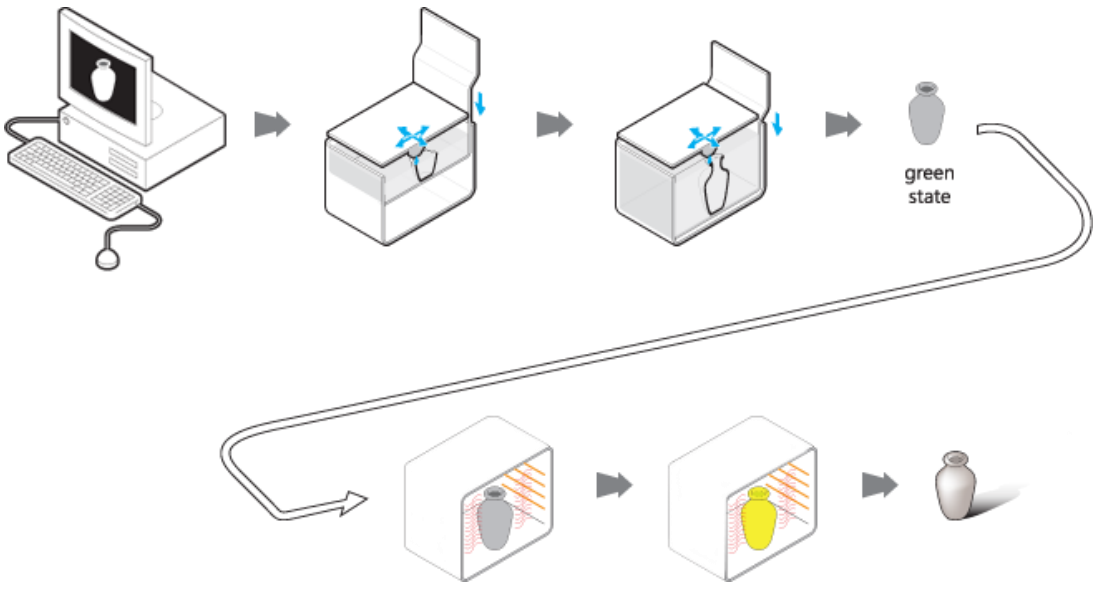


Figure 37: Ceramic 3D printing methodology, incorporating Z Corp printing technology, schematic representation of the 3D printing process (Imaterialise, 2014c). The model is built layer by layer (green state), then placed in a drying to gain strength, and then glazed and cured in an oven again.

Figure 38: 3d printed ceramics inspired by Southwest Native American pottery. Available from: http://www.washington.edu

Glass printing is similar to the process for metals. Glass particles are bound with organic binder and oven cured. Following the firing over 750 degrees Celsius the binder evaporates and the object's density increases. The temperature dictates the porosity of the final product. This feature is similar to normal glass production. At low firing temperatures, the density is higher. Shrinkage about 10% is observed after firing. The material is not smooth as regular glass is. The resulting material can be opaque or translucent frosted white. The 3d printing of completely translucent glass is not possible yet. Its surface is porous and rougher, though a smooth and shiny appearance is achieved by a process of glazing (Marchelli *et al.*, 2011). The research is directed to the printing of multi materials and heterogeneous materials. The various parts of a product's geometry will have different properties without the need to re-assembly (Huang *et al.*, 2013; Zolfagharifard, 2013).

2.3.2.5.1.4 Post processing

The 3d printed parts can be further processed so as to acquire the desired properties, mainly its optical properties and its strength. The amount of processing depends on the 3d printing technique, resolution and print time as well as on the requirements of the 3d printing project. Usually the first post

processing operation is the removal of support structures and excess material. Polishing, glazing and dying are among the most common post processing. Dying, by immersing the model in a bath containing colour pigment, is a manual process that includes washing of the model, preparation of the pigment and dissolving it into warm water, and finally immersion of the model for almost 20 minutes. It is also possible to paint the model using a spray paint, where the colour tone and the glossiness/reflectivity of the surface can be determined. Also, glazing can be applied to the surface as well as polishing by mechanical smoothing. Although post processing may enhance the optical properties, surface detail may be lost and edges will be rounded. Post processing operation may require more time than the actual 3d printing. Electro-plating, sealing and chemical treatment enhance the mechanical properties, adding strength and durability to the printed pieces (Creatz3D, 2015) (Figure 39).

Figure 39: The excess powder is removed from the chamber using a vacuum (left), and a binding agent is applied over the entire 3D print to add stability (right). (Vaughan, 2012, Figures 14.5 and 14.6). Available from: http://www.graphics.com/article-old/fundamentals-3d-printing-digital-models

2.3.2.5.2 Applications

2.3.2.5.2.1 Archaeological applications

3D digitization and 3D printing provides an alternative methodology, which employs not only non-contact operations, in accordance with preventive conservation standards, but also accurate, affordable and easy methodologies

for replication (see section 2.2.1 for a discussion on preventive conservation problems including handling and replication issues).

3d printing is not a new technology, as demonstrated by the earlier applications of stereo lithography in the cultural heritage sector (Arnold and McAllister, 1998). Advances in computing power, new design software, new materials and affordable cost have resulted in its rapid development (Lipson and Kurman, 2013). Characteristic examples are the applications of rapid prototyping for archaeofaunal remains (Niven *et al*., 2009) human skeletons (Allard *et al*., 2005) sculptures (Arnold and McAllister, 1998; Fowles, 2000; Happa *et al*., 2009; Earl *et al*., 2009; Wachowiak and Karas, 2009; Celani *et al*., 2009) (Figure 40), and architectural parts (Richens and Herdt, 2009), delicate objects, such as the Ferryland cross (Logan *et al*., 2010) and cuneiform tablets (Lipson and Kurman, 2013). The exhibition *3D: Printing the Future*, at London's Science Museum, where 600 3d printed items are on display, is a wonderful opportunity to explore the future possibilities that 3D printing might offer to museums. Moreover, the Smithsonian exhibition *"Slavery at Jefferson's Monticello: Paradox of Liberty"* presents a 3d printed life-size statue of Thomas Jefferson (Institute of Industrial Engineers, 2012) (Figure 41).

Figure 40: Marble relief from the Garden Temple at Ince Blundell Hall, Merseyside, original (left) and 3d printed replica (right) (Fowles, 2000, p.90-91)

Figure 41: Exhibition Installation of Slavery at Jefferson's Monticello: Paradox of Liberty. Available from: http://nmaahc.si.edu

2.3.2.5.2.2 Applications in conservation

These advantages are of great importance in replication of artefacts, but there is also a strong potential in the area of computer-aided reconstruction and rapid prototyping/3d printing for restoration and gap-filling of artefacts (see section 2.2.2.3 for a discussion on gap filling problems). Virtual reconstruction and replication of missing parts can be a more effective methodology for artefact restoration, as it overcomes problems encountered with traditional approaches. The main advantage is that the whole operation is executed in a controlled virtual environment providing results much more accurate than manual approaches. It is totally non-contact, throughout the process, from data capture and processing to 3d printing of the missing fragment, enabling the reconstruction and/or replication even for fragile vulnerable artefacts. There is the option of creating attachable parts, with specific geometric characteristics, in order to fit the original artefact without adhesives.

This is a promising methodology for solving the gap filling problems, and adequate testing is needed, because, although it could be used in reconstruction of the works with a controllable level of fidelity to the original (Taylor *et al.*, 2002), its contribution in restoration treatment is limited. A wooden support from a church at Rothenstein in Germany was badly damaged by insects, and remained a wafer-thin layer of wood, unable to fulfil its structural goals. The digitization and milling of the new material provide a replacement support capable to fulfil its goal (Ioannides and Wehr, 2002).

The missing part of the digital model of a badly damaged medieval skull was virtually reconstructed and the custom-designed model was directly fabricated by means of the RP process. Virtual or physical reconstitution of hominid fossil skulls, discovered in different regions of the world, help palaeo-anthropologists to reconstruct the genealogic tree of the evolution of man and to better understand, the diversity of the Homo Erectus species (Fantini *et al.*, 2008) (Figure 42).

Figure 42: Reconstruction of a medieval skull with 3d printed missing part (Fantini *et al.*, 2008, p.323)

Another project aimed at the restoration of the Opus sectile floor in the chapel of St. Restituta. 3-D laser scanner technology and rapid prototyping enabled the creation of a virtual model in resin of the imprint of the flooring upon which the recovered slabs and tesserae can be placed (Casaril *et al.*, 2006). Moreover, 3d printing was used in the large scale conservation projects of the reconstruction of a fifteenth-century ship. The material used to make the 3d print was chosen to have similar elastic and plastic deformation properties as the original wood and could therefore be employed under similar stresses (Soe *et al.*, 2012) (Figure 43).

Figure 43: 3d printed model of the Newport Ship (during build) (Soe *et al.*, 2012, p.444)

Apart from replication and restoration 3d printing can also contribute in the examination of artefacts. An interesting application is the combination of medical 3D imaging with rapid prototyping techniques in forensic Imaging (Ebert *et al.*, 2011). Conservation can benefit equally from 3d printing, as the replication can be combined with advanced imaging technologies in order to fabricate not only the artefact's surface but also its internal structure. Three dimensional technology enables the capturing of 3d, volume, texture and

colour as well as data beyond the visible (these methodologies will be discussed in 0). With 3d printing these data can be linked to the physical world. The advantages of this strategy are the more efficient examination and interpretation of data. Moreover, the physical 3d printed model can serve as a replica of the artefacts' structures, which is not subjected to the degradation in the same rate as the original one. Considering that academic institutions consist of the one-third of 3d printers market (Jones, 2012), we expect the broader application of 3d printing in research in the near future.

One of the most critical aspects for the application of 3d printing for conservation purposes is the 3d printing materials. This is of interest in 3d printing of artefacts for replication and manufacturing of internal structures. By applying special treatment, post-finishing steps and materials the creation of a model with specific optical properties is possible, although the cost will be higher. The texture, the weight, the temperature can be adjusted to resemble the original, so as to create a convincing replica, but the material composition and the ageing properties cannot be controlled. The 3d printed materials should be tested in advance before applied to fragmented artefacts. Considering that these materials are rather new, they have not been tested and their ageing properties are not fully identified yet[14]. This issue becomes a very crucial factor in case of 3d printing of missing parts of artefacts for restoration purposes, because the printed object is in contact with the original fragmented artefact. The requirements for materials to be used as fillers in objects restoration should be taken in to consideration. In general important features are the aesthetics of the restoration, its reversibility and re-treatability, as well as the strength, density, durability, shrinkage and thermal expansion of the filler. The long lasting performance of the filler, which should not be subjected to physical and chemical changes, nor interact and contaminate the original fragmented object, is essential.

[14] It is assumed that modern plastic 3d prints degradation might be similar to other plastic material, but there is no evidence for this. For plastics degradation in museums collections see (Shashoua, 2008).

A case study on the use of 3d printing in remedial treatment is presented in section 6.3 and 6.4.

2.3.3 3d documentation

Nowadays, the principle of documentation of aims, processes and results for future conservation and examination is well understood and appreciated. As a result, research is focussed on a relatively long list of three-dimensional techniques for recording, as well as a number of computational photography tools. These techniques made it possible to document and integrate the many forms of documentation. The documentation is closer than ever to environmental documentation, which is a combination of the various scientific documentation approaches (Addison *et al*., 2005). Table 3 presents the most widely used traditional documentation techniques and their digital analogues.

Table 3: Conventional documentation and digital analogues.

Conventional	**Digital**
Sketches , drawings	Non-photorealistic rendering, Algorithmic rendering
Photography	Computational imaging, 3d digitization
Casting	3d printing
Paper documentation	Scientific workflows, provenance, systematization

3d-digitazation transfers documentation to a new level of excellence, as demonstrated by earlier applications of 3D computer graphics in cultural heritage (Callieri *et al*., 2005). 3D recording is a more efficient method for documentation and dissemination, not only because 3D models can be presented in many ways, as still images or animations, but also because the user can acquire the chosen view from a variety of angles interactively. It is suggested that digital methods are more objective and accurate than traditional ones. Digital records are influenced by known computational and user limitations, while traditional techniques depend on unpredictable human perception. Therefore, the resulting datasets are more sustainable and of

greater value to subsequent researchers (Richens and Herdt, 2009). A comparative analysis between traditional and digital documentation strategies leads to the safe conclusion that digital tools perform better in terms of efficiency, accessibility, provenance, systematization and versatility. Considering the objective of practicality, affordable, easy and practical digital documentation options are available, but simultaneously there are high-cost techniques, whose execution is difficult.

Unlike traditional recording techniques, 3d models can be enriched with online explanations so as to link the spatial representation of the 3D shape with other related information (Echavarria *et al*., 2012) (Figure 44). However, the semantic annotation of 3d data is not yet standardised, and the vast majority of 3d annotation refer to a problematic geographic definition of the 3d model, and by extension the original artefact. Most of them refer to 3d points or whole objects, while there is a clear need for adding annotations to points, segments and surface regions of 3d objects. The 3DSA (3D Semantic Annotation) system, based on the Open Annotation Collaboration (OAC) data model, includes features for adding exchangeable and re-usable annotations to points, surface regions or segments of 3D digital artefacts. This project, focused on 3d semantic annotation for 3d models of cultural heritage, managed to provide a useful tool for annotation and comparison of museum objects and artefacts, by assigning relationships between the different aspects of objects, such as dimensional comparison (Yu *et al*., 2011; Hunter and Gerber, 2010) (Figure 45). The 3d annotation can provide a better understanding of objects' condition compared to traditional condition reporting. According to Echavarria (2012, p.46), 3d annotation '*has the potential to provide heritage professional, looking at the preservation of these monuments and sculptures, a more effective tool to assess their risk and take further actions if needed*'. For that reason the annotated 3d space allows the user to open different version of the 3d model, representing the artefact in different condition and annotate them accordingly. This functionality is not only useful for preservation, monitoring and condition reporting, but can equally enhance remedial conservation operation documentation. In that sense the historical record of the object visualised in 3d form can be tracked and annotated for future investigation, as well as for evaluation of treatment.

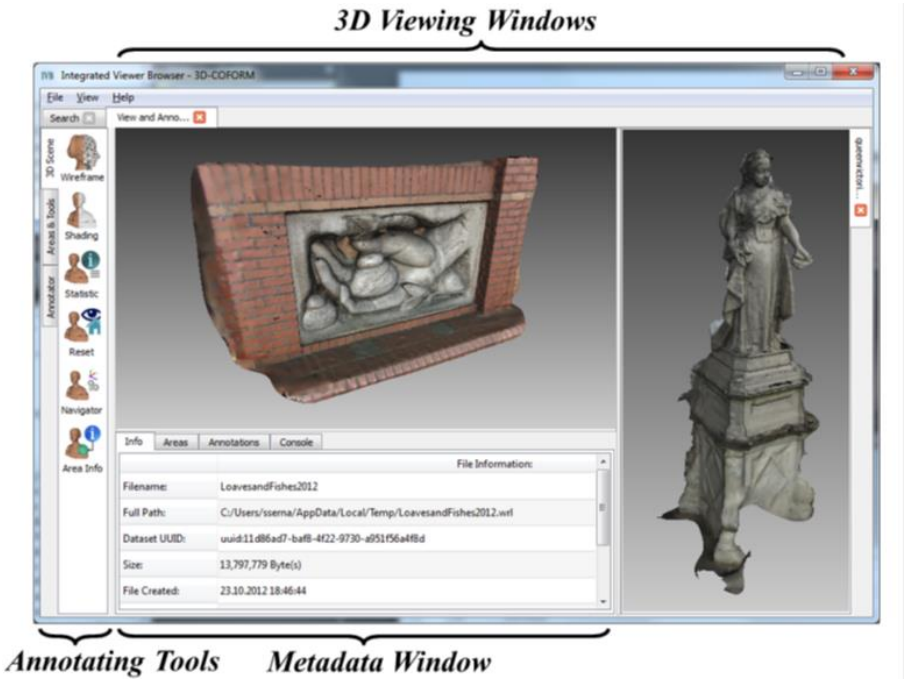


Figure 44: Annotation interface (Echavarria *et al.*, 2012, p. 46).

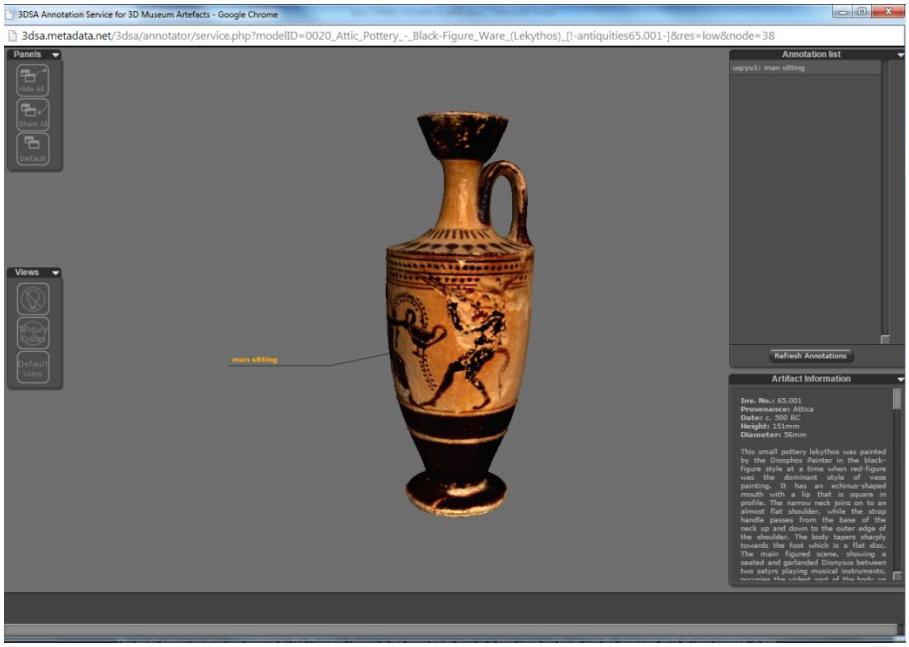


Figure 45: 3d model of an Attic lekythos viewed in 3dsa gallery. Available from: http://3dsa.metadata.net/3dsa/

Three-dimensional digitization offers the opportunity of ultrarealistic and/or non-photorealistic rendering. The former is the advanced digital analogue of photography while the latter is an alternative for drawings and archaeological illustrations.

2.3.3.1 Non-photorealistic rendering (NPR)

The archaeological illustrative tradition and the contribution of illustration in documentation (shape, decoration and surface details), explanation of form and function as well as interpretation makes illustration a positive, if not necessary, addition to conservation reports. However, traditional illustrations are lacking in accuracy and are influenced by subjective judgement, resulting in documentation problems as discussed in section 2.2.3.3 (see also A.2.2). NPR emerged during the 1990s, as the opposite of photorealistic rendering, having as a goal to imitate traditional illustration (Rusinkiewicz *et al.*, 2008) (Figure 46). Since then considerable progress has been made towards reproducing traditional pen-and-ink techniques for rendering 3D objects (Isenberg *et al.*, 2006). While NPR attributes of artistic creativity and aesthetics have been discussed, for the purposes of conservation and artefact studies it is the comprehensibility and clarity that stands out as the most distinguished features. Line drawings are the simplest NPR technique. The basic elements of line drawings are silhouettes or contours, with creases and suggestive contours. The most common used drawing elements are the hatching and stippling (Rusinkiewicz *et al.*, 2008) (Figure 46).

Figure 46: The basic elements of line drawings; silhouette, contours and suggestive contours (from left to right). Available from: http://gfx.cs.princeton.edu

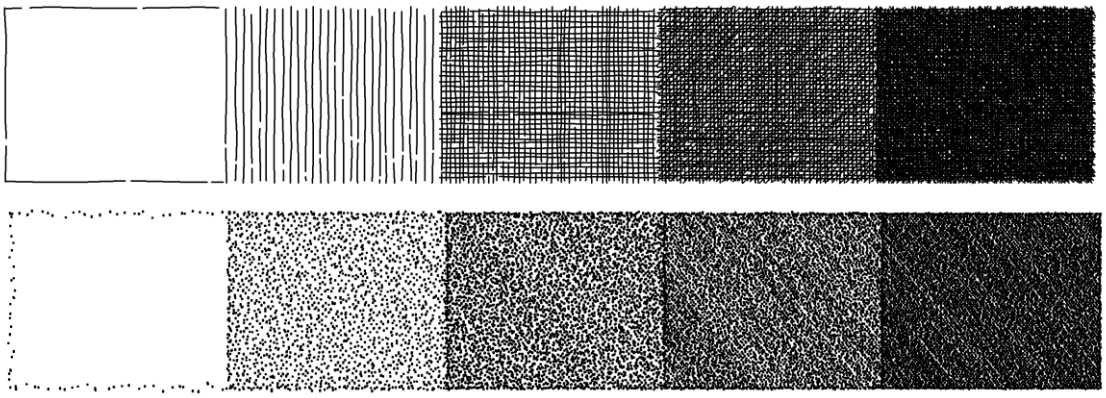


Figure 47: Cross-hatching, and stippling (Winkenbach and Salesin, 1994, p. 93).

The stronger advantage of NPR over traditional drawing is the enhanced description of detail and the clear depiction of shape, resulting in tighter images with a less sketchy look. NPR provides a realistic and three-dimensional looking drawing, because of the better shading and lighting, as well as the highly detailed stippled and/or cross-hatched images. Hence the better illustration of complex artefacts, difficult to achieve with traditional drawings, is possible (See section 5.4.2.3 for examples). Also notable is that NPR is able to simulate archaeological illustrative tradition. The most commonly used elements of traditional drawings, hatching and stippling, can be reproduced. Contrary to traditional illustrations, NPR is flexible, being able to provide illustrations of digitised artefacts in various forms for different purposes (e.g. book, poster, display). In that way, different aspects of the illustration become apparent to viewers, and might lead them to different conclusions about the objects. Different parameters can be applied to the portrayed information for changing viewing contexts.

Nevertheless, computer generated illustrations have been criticised for being too perfect and sterile due to less variation in their lines or stipples. Moreover, the expertise needed is not yet considered a standard skill for museum professionals, although the new generation of archaeological illustrators is familiar with these techniques. It seems likely that the future of archaeological illustration is the NPR techniques, due to their ability to provide improved communication of information. Algorithmic rendering (AR) is one of the most promising future techniques.

2.3.3.1.1 Algorithmic Rendering

Algorithmic Rendering (AR) is a computational photography tool and an NPR technique, currently under development, and is complementary to RTI, since both techniques share the same data sets. The final outcomes of the project would be an open source tool, able to provide a variety of different illustrations, underlining different features of the photographed surfaces. Merging and mathematical transformation of the data in the form of image sequence, results in an information-rich visualization and a new digital representation, in accordance with cultural heritage recording and documentation needs. The resulting visualization cannot be compared to any individual image. Important features are presented in a new and useful way, assisting the examination of artefacts and leading to an advanced perception of three-dimensionality, surface shape, detail, material, and colour (Cultural Heritage Imaging, 2012).

A sequence of images with reflective spheres under different illumination is being captured. The AR process generates images with Red, Green, Blue, and Normal information (RGBN images) with per-pixel colour and surface shape information. The RGBN information is being processed using signal processing "filters", resulting in a variety of different visualizations of the same dataset, useful for the documentation of complex objects. The processor of AR, based on non-photorealistic rendering of RGBN data, was developed at Princeton University (Toler-Franklin *et al.*, 2007).

The "Automated Documentation and Illustration of Material Culture through the Collaborative Algorithmic Rendering Engine (CARE)" project by Princeton University and Cultural Heritage Imaging (CHI) will result in an open source tool, the Collaborative Algorithmic Rendering Engine (CARE), able to create accurately rendered drawings from the same photographic data sets that are used in Reflectance Transformation Imaging (RTI). Having as advantages minimal user effort, cross-site collaborative visualization design and provenance data tracking, the CARE will overcome problems in the field of digital cultural heritage. RGBN images are less computationally expensive, considering storage and time, in comparison to 3D models, while they represent three-dimensionality efficiently.

The AR technique is not yet released; as a result the published examples are limited and originate from the original research of Rusinkiewicz and Toler-Franklin, provided by CHI (Cultural Heritage Imaging, 2012). The principles and ideas of AR have been presented (Mudge *et al*., 2008; Schroer and Mudge, 2012) and the application of this technology is believed to lead digital cultural heritage applications to a mature level and contribute to conservation as well. The automatic application of different signal processing filters on the RTI dataset will result in different representations. In the example of the Sennedjem Lintel from the Phoebe A. Hearst Museum of Anthropology at the University of California six different illustrations are available. Exaggerated shading reveals fine surface details, the darkening groves emphasizes large features, "toon shading" depicts shape features, "Labertian shading" computed on the grayscale image conveys surface shape and suggestive contours present another method conveying shape. The petroglyph example from the Legend Rock Site in Wyoming demonstrates the ability of AR's "Exaggerated Shading Technique" to enhance details covered by patina. The mathematical transformations will not be limited to colour information, such as image-processing software, but will include the rich surface-structure information contained in the surface normals. The user will choose from the list of the available filters and will be able to adjust the parameters of each filter and combine them, in order to create an adequate illustration for the imaged object (Figure 48). The CARE will provide the necessary provenance data for the created illustrations (Cultural Heritage Imaging, 2012).

For the purposes of this thesis new NPR and image enhancement approaches have been developed (Chapter 5).

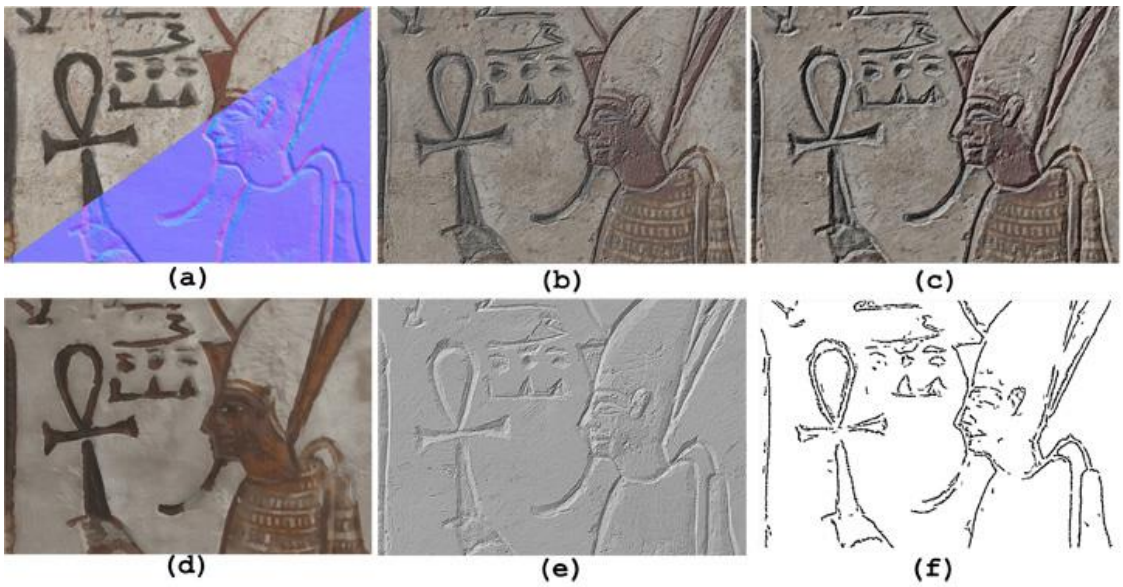


Figure 48: The Sennedjem Lintel from the Phoebe A. Hearst Museum of Anthropology at the University of California, Berkeley. (a) AR composite image with color and surface normals at each pixel. (b) Exaggerated shading reveals fine surface details. (c) Darkening groves emphasizes large features. (d) Toon shading depicts shape features. (e) Labertian shading computed on the grayscale image conveys surface shape. (f) Suggestive contours present another method conveying shape. Illustrations by Dr. Corey Toler-Franklin. Available from: http://culturalheritageimaging.org

The most widely used method for systematization of documentation is the collection management systems in the form of databases, which are searchable and provide opportunities for fast and easy comparative analysis and statistics, and encourage communication of conservation related information. Conservation related documentation is sometimes a part of the collection management system, although conservation specific systems have been developed and are in use in many museums and cultural organizations. Questions arise as to whether these systems can meet the needs of conservation in terms of 3d recording and documentation.

2.3.3.2 Scientific workflows

There is no doubt that the contribution of computers and communication technology in scientific research methodology is increasing, and digital

components are now integral parts of research. Apart from digital preservation (section 2.2.3.4) the need for automation becomes apparent because of the quantity of scientific digital data, their complexity and the need for systematic analysis of results. Many and diverse scientific disciplines, involved in acquisition, manipulation and processing of large amounts of complex data, have already introduced scientific workflows in research practice, in order to overcome this problem. Workflows can be characterised as the coordinator of a multi-task process, where task is software and process is a series of structured activities, accompanied by appropriate documentation. Experience proved that workflows can provide a solution in scientific problem-solving and decision-making. This is achieved by *in silico* experimentation, cross-checking of results and run simulations with various datasets from different sources. Workflows enhanced scientific cooperation, because they can be reused, avoiding reinvention. The lifecycle of a workflow is the following: design, setup, execution, monitoring, refinement, share and reuse.

2.3.3.2.1 myExperiment, Open Provenance Graphs

The Virtual Research Environment myExperiment (Goble and De Roure, 2007) was developed in order to support and facilitate free sharing of workflows, methods and data among scientists on the web. The assistance provided by myExperiment is a valuable and useful tool for the successful retrieving of data among well characterised and established methods. In a context like this the scientific community is concerned more than at any other time in the past for the provenance of data. Open Provenance Model (OPM) (Moreau *et al.*, 2011) explains and describes the processes in which digital data and things with a physical existence have been involved, and which results in their present state. The co-presence of digital and physical data is of great value for conservation documentation. According to OPMs visual representation, artifacts (=physical or digital objects-DEF1) are represented as ellipses; processes (actions-DEF2) as rectangles and agents (catalysts of a processes-DEF3) as octagons. Dependencies or causal relationships between artifacts, processes and agents are represented by arcs or edges, where the source is the effect and the destination points the cause (DEF4). These relationships can be:

- used by (DEF5)
- was generated by (DEF6)

- was triggered by (DEF7)
- was derived from (DEF8)
- was controlled by (DEF9)

The processes can be further explained by roles assigned to edges (DEF10). Roles are required in case of 'was Generated By' and 'was Controlled By'. Provenance graph can present different levels of details. More and less detailed descriptions of processes can coexist. In a pair of such overlapping accounts, the more detailed sub-graph is called refinement of the other. An OPM Graph can optionally include time annotations (Moreau *et al.*, 2011) (Figure 49). OPM graphs are used in order to document the novel methodologies proposed in this thesis (Chapter 5-6).

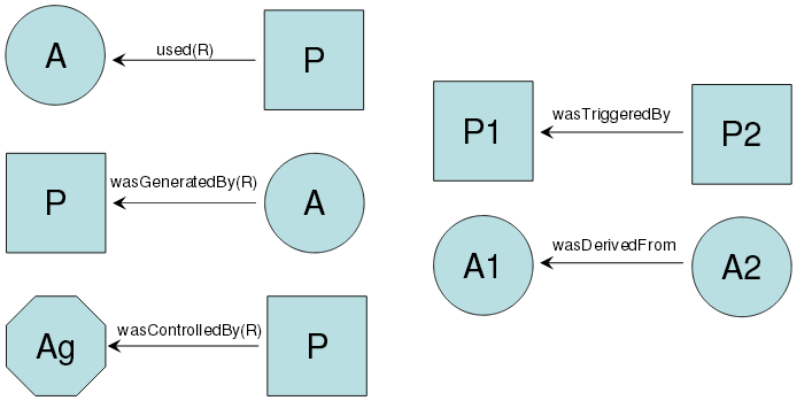


Figure 49: Representation of artifacts, processes and agents and their possible relationships (Moreau *et al.*, 2011, p.744)

2.3.3.2.2 CIDOC-CRM

The CIDOC Conceptual Reference Model ("CRM") is an object-oriented domain ontology able to formalise the semantics of museum archive documentation and enhance heterogeneous data interchange. The CIDOC CRM consists of superclasses, classes and properties hierarchy, enables the integration of information from different sources, is flexible and extensible, empirical and descriptive (CIDOC-CRM, 2014). Ariadne Conservation Documentation System,

developed in the department of Conservation of Antiquities and Works of Art (SAET), Technological Educational Institution (TEI) of Athens, incorporates the CIDOC CRM concepts and relationships (Naoumidou *et al.*, 2008) (Figure 50). The guidelines for labelling and marking, as well as registration of objects in museums, are also of great help and can serve as a basis for the definition of the conservation CIDOC-CRM.

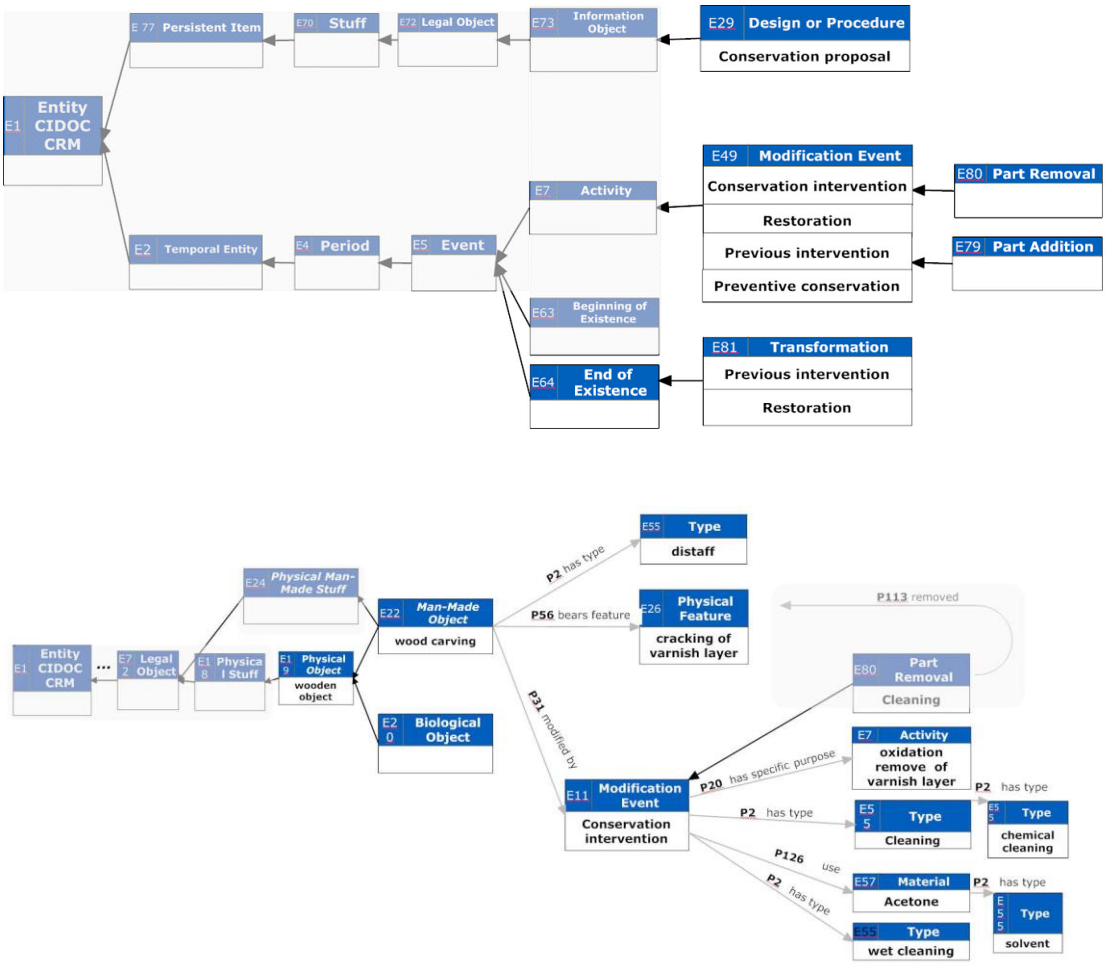


Figure 50: Example of Ariadne's entities as instances of the CIDOC CRM (Naoumidou *et al.*, 2008, p.8-10).

2.3.3.2.3 3D-COFORM

The EPOCH research agenda was dealing with issues of documentation and standardization, relevant to those discussed above. The aims of the project, among others, are the definition/classification of shape characterization in representations for CH, the definition of a sustainable 3D file format and

methods for generic, stable, and detailed 3D mark-up as well as 3D querying, provenance and processing history (Arnold and Geser, 2008). The annotation scenario of the 3D-coform project aiming at establishing links between 3D artefacts, bibliography or any other multimedia information about the artist or the object is of particular interest for conservation documentation. In the annotation scenario of the V&A museum, the following operation sequence was proposed (3D COFORM, 2013):

- 3d acquisition (secondary 3D artefact)
- Restoration
- 3d acquisition (primary 3D artefact)
- Conservation reporting in the form of annotations in the 3d models
- Add links between the two 3d artefacts. In future scans new annotations are used to describe differences over time.

2.3.3.2.4 The Digital Lab Notebook

The digital lab notebook is a tool under construction by CHI which is expected to assist metadata management easily and in accordance with everyday working principles and digital tools. In that way, the records are more scientifically reliable and can be further used and better preserved for future use and re-use. A core feature of the digital lab notebook is the '*digital provenance*' or '*empirical provenance*', which includes metadata and processing history of digital representations, providing an advanced understanding of their role and, in that way, increasing their impact on the scientific community. The digital lab notebook can be beneficial for the quality, the accuracy and acceptance, collaborative distribution of digital surrogates avoiding false interpretations and considerably improving documentation (Cultural Heritage Imaging, 2013a; Mudge *et al.*, 2008; 2007). The digital lab notebook is expected to revolutionise research and lead documentation to an advanced level.

2.3.3.2.5 Patina of Notes (PoN)

PoN is an information management system, accessible through web browsers on computers and smart phones, part of the PATINA project. Through PoN

researchers can collect, organise and browse their data, which can be linked to open form notes and notes, keeping track of the provenance of information (Costanza *et al.*, 2013; Jewell *et al.*, 2012).

2.3.4 Mixed reality approaches

In the previous sections the usefulness of digital technology in solving conservation problems is discussed, where the digital artefact is one of the main components alongside the original. The distinction between digital and real artefact is that the latter can be experienced with senses other than the visual, i.e. sound, smell and touch (Newell, 2012). With the tremendous advances in computer science there is a broader application of virtual reality and computer graphics in museums. Contemporary museum activity includes new media in a transformed democratized museum environment that encourages deeper engagement between visitors and artefacts (Henning, 2008). Among the most widespread methods and tools are the advanced imaging strategies for digitization and Web3D, including either the virtual, augmented and mixed reality[15] exhibitions or handheld devices (Sylaiou *et al.*, 2009).

There is no doubt that conservation can benefit from bridging the gap between the physical and the digital via augmented and mixed reality technology. Digitization brings the physical artefact closer to the conservator, by enhancing examination, analysis and documentation, and by providing assistance in conservation dilemmas. Three dimensional reconstructions and reproduction made possible the execution of operations considered as impossible by earlier generation of conservators, such as the digital refitting and replication. In the 21st century the goal is to bring the virtual into closer alignment with the physical world (Lipson and Kurman, 2013). This from a

[15] Augmented reality (AR) refers to a system in which the user views and acts within an enhanced version of the real world. The enhancements are virtual (computer-generated), and can include objects or information. Mixed reality (MR) refers to a system that combines real and virtual objects and information (Bowman, 2008).

conservation perspective applies to the virtual execution of operations and to the blending of the virtual and the physical. In that way the virtual artefact may inherit some values form the original and the original may be enhanced by digital elements. Huge steps have been made towards the virtual execution of operation, regarding micro-excavations, fragments matching and condition recording. Considering that conservation operations are interactive processes executed on non-static physical objects, they are highly unlikely to be transformed into the virtual space using static and stable visual representations. On the contrary, the blending of the physical with the virtual can be potentially realised by means of tagging, 3d projection, haptic and 3d printing technology. Although these technologies have been used in museums, they have never been applied in a way that befits conservation objectives.

The advances of digital technology signal an opportunity to meet a compromise between access and preservation. Mixed reality, 3D modelling and 3D printing have significant potential to provide working solutions to the preservation versus use dilemma. Recently, because of technological advancements, these technologies are more easily adopted, and provide solutions which would be impossible using conventional methods. In that sense Clavir's (2002, p.64) questions '*whether "museum use" necessitates physical use or whether its intention can be accomplished in a manner more compatible with preserving the physical object*' needs to be revisited. This thesis argues that there is a way to achieve this by means of digital technology.

In the following sections three main attributes of mixed reality approaches that can be adopted by conservation; haptic technology, tagging and projections, will be analysed and examples from the current practice will be presented.

2.3.4.1.1 Haptics

Haptics provides an innovative form of interaction between humans and information (Bergamasco *et al*., 2002), increasing the ability to conceptualize 3D shapes, by imitating the forces that we would feel if we physically interact with the object, in either virtual or mixed environments (Butler and Neave, 2008). Zimmer and Jefferies describe haptic and original 3d artefacts as an analogy to a picture and its digitised version (Zimmer and Jefferies, 2007).

Haptics *'allowed the freedom to trial ideas and explore through the artistic process'* because even *'If the artist wishes to change their mind with regard to an aspect of the art piece, they are free to do so'* (Butler and Neave, 2008, p.135). In other words this technology provides the ability *'to feel textures and shapes of virtual objects, modulate and deform objects with a very high degree of realism'* (Brewster 2005, p.3) (Figures 51-52).

Figure 51: 3-D tactile experience of museum objects, which enables blind and visually impaired museum visitors to 'touch' 3-D scans of museum artefacts, presented with multimedia information support. Available from: http://zeroproject.org

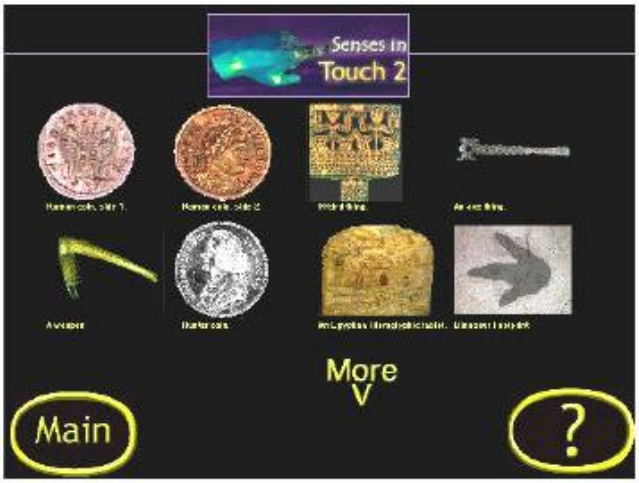


Figure 52: The Senses in Touch II exhibit, developed by the the Computing Science Department and Hunterian Museum at Glasgow University, enables the

haptic experience of objects such as coins, engraved Egyptian hieroglyphics and the cast of a dinosaur footprint (Brewster, 2000).

For example the PHANToM system could resemble the feel of a three dimensional object from all sides, imitating the physical contact (Zimmer and Jefferies, 2007) (Figure 53). Another interesting application, with strong impact on transforming the virtual haptic object, is the integration of a Chinese calligraphy brush as a 3D interaction tool (Song *et al.*, 2005). Moreover, Bergamasco (2002) discusses the ability of such virtual environments to recover information about other objects that are related in a way to the object under haptic exploration. In conservation this technology has found limited use, focused on training (Geary and Sandy, 2004) (Figure 54). Potential uses of haptics in conservation are presented in section 4.2.2.1.

Figure 53: Haptic devices; Phantom Omni, desktop and premium by Sensable technologies. Available from: http://www.dentsable.com

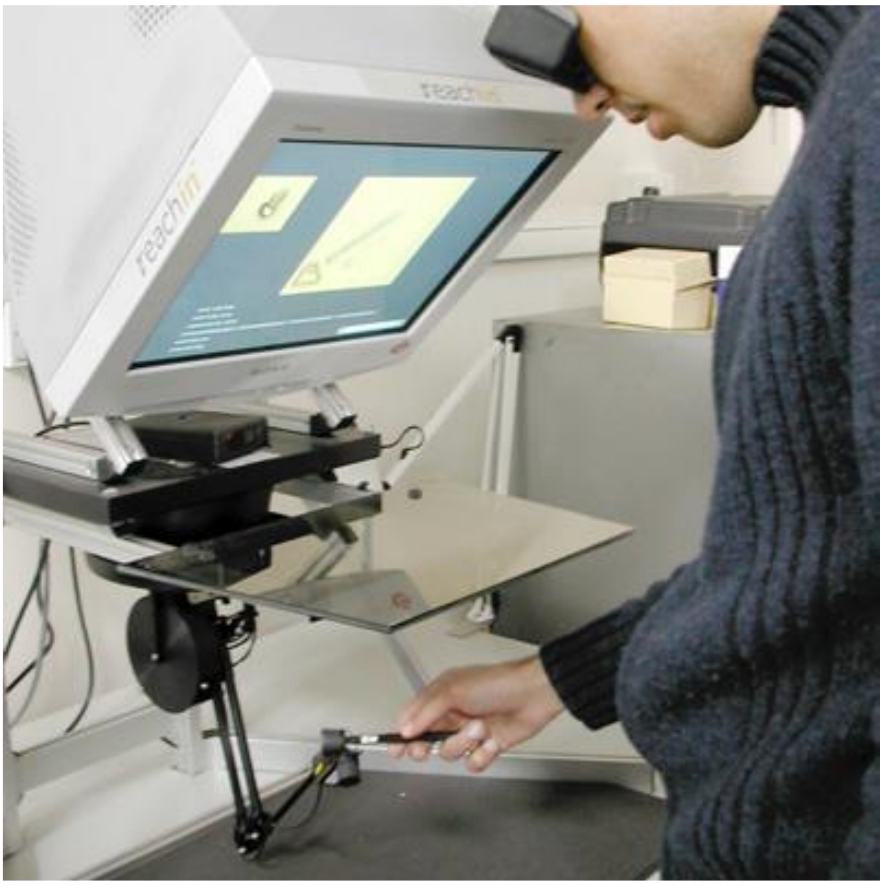


Figure 54: Using haptics in conservation training. A backing removal simulation environment and interface created for paper conservation training (Geary and Sandy, 2004, p.429).

2.3.4.1.2 Automatic identification data capture techniques (AIDC)

The connection between the virtual and the physical world has been explored by researchers by means of automatic identification and data capture (AIDC) techniques. They enable fast, easy and accurate data collection methods, storage and analysis of the data. AIDC methods include technologies such as barcodes, Quick Response codes, Radio-Frequency Identification (RFID) and Near Field Communication (NFC).

1D barcodes are universally recognized codes used in our everyday life because of their speed and accuracy. Their disadvantage is limited space for storage. This lead to the development of 2D barcodes, referred to as quick response (QR) codes by Denso Wave Corporation in 1994. QR codes contain information in both directions and are able to encode several types of data.

They can be generated easily online and printed on low cost printers with normal paper. OR codes can be accessed easily using mobile phones or QR code readers, which displays, manipulates, or stores the information. QR code can store 7,089 characters for numeric data, 4,296 characters for alphanumeric data or 2,953 bytes for binary data. Another AIDC method is the RFID, which stores and retrieves data from an identification chip by means of radio waves. It is a short-range wireless communication type, useful for distances less than 100 meters. Near Field Communication (NFC) is an AIDC method, similar to RDIF that falls in the category of short-range high frequency wireless communication technology. Contrary to RDIF, NFC can be used in distances less than 10 cm, providing a more secure option (Vazquez-Briseno *et al.*, 2012).

The industrial use of QR Codes and RFID/NFC tags has been increased in the last few decades. Nowadays, their use in other fields is explored so as to link the physical world with the virtual one, and enhance the interaction between people and things. The contextual QR codes aim to personalise the information to each user of the code according to the location, time, and kind of device detected, environment and task. The specific information displayed to each user is an enhanced option for the development of the tasks. According to Rouillard (2008, p.54) the context-aware features '*is a way to capture and distribute a tremendous amount of information in a simple, quick and efficient manner*'. Object hyperlinking is another way of linking the physical and the virtual world. Tags on physical objects with, that contain a URL, drive the user to digital data and online resources about objects (Vazquez-Briseno *et al.*, 2012).

RFID/NFC and QR codes have been used to enhance visits to museums. For example these technologies were used in the Louvre (Figure 55), the Stuttgart's Mercedes-Benz Museum, the Genoa's Wolfsoniana Museum, the National Museum in Krakow and the Musee du Quai Branly in Paris. The Tales of Things, a collaborative project among several universities in the United Kingdom, connects the physical objects with digital data by means of QR codes and mobile devices. Tales of Things tags had been employed in museums, so as to help visitors interact with objects and express their opinion about the exhibition (Weber and Weber, 2010). The exhibition Scotland: A Changing

Nation displays 80 objects, tagged with QR codes, enabling visitors to add their own data via the Tales of Things Website (National Museums of Scotland, 2014). The QRator, a joint project with UCL Centre for Digital Humanities, Centre for Advanced Spatial Analysis and UCL Museums, follows the ideas of the Tales of Things by allowing members of the public to add their own comments about museum objects (UCL, 2011) (Figure 56). Potential uses of tagging in conservation are presented in section 4.2.2.2.

Figure 55: RFID/NFC and QR codes for the iconic painting of La Gioconda, Louvre Museum (uQRme, 2013).

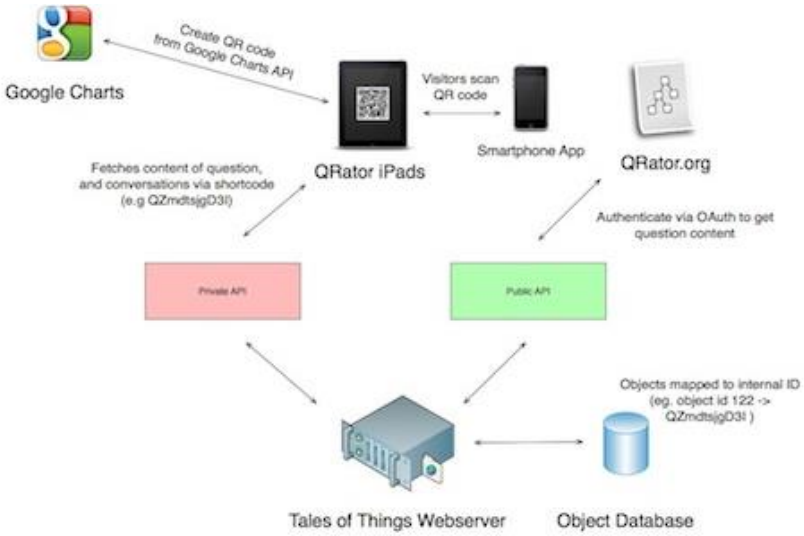


Figure 56: QRator System diagram (Gray et al., 2012).Available from: http://www.museumsandtheweb.com/mw2012/papers/enhancing_museum_narratives_with_the_qrator_pr

2.3.4.1.3 Perspective corrected projection

In the previous section techniques that allow retrieving data, interaction and information exchange between the physical object and digital records via mediating devices, such as mobile phones, have been presented. In this section projections on physical objects are being discussed in an attempt to augment the physical artefact by blending it with the virtual one. Three-dimensional projection, based on the further development and combination of existing technologies, has been considered an evolutionary type of mixed augmented reality (Dalsgaard and Halskov, 2011).

The uniform or diffuse reflectance and the planar, multi-planar or simple parametric geometry of conventional screens used for display guarantee image quality. But in the case of projections on physical objects the absence of ideal reflectance and geometry may lead to colour, intensity and geometry distortions, in the form of inter-reflections, diffuse and specular reflections, regional defocus effects, refractions. Computer vision techniques and computer graphics approaches need to be implemented so as to overcome such problems. Geometric distortion of projected images can be solved with geometric projector-camera registration techniques. Projective texture mapping is sufficient for uniformed coloured surfaces but more precise registration techniques, geometric warping, radiometric compensation, multi-focal projection, and the correction of general light modulation effects, are required for textured surfaces with complex geometry and spatially varying reflectance, colour and intensity (Bimber *et al.*, 2008).

The precise calibration of the projectors and lighting is a difficult task in a museum environment, and this is one of the most challenging aspects of its application in cultural heritage. Three dimensional projections were mostly used to augment or transform the built environment, and to a lesser extent to objects. Their main contributions are to enhance or emphasize physical aspects of objects to transform their materiality. Using different strategies the simple physical content can be enhanced with complex virtual elements or vice versa, while the virtual and the physical elements can be fully or loosely connected (Falck and Halskov, 2013).

In the case of Holger the Dane researchers brought the statue into life by presenting the legends about the statue by means of 3d projections. Making use of computer graphics techniques they manipulated the shadows of digital elements projected on the statue, creating interesting illusions. Moreover, particle systems created realistic effects, for example the reflections of the simulated fire and dust on the statue. The use of 3-D projection transformed the perception of space and materials. Visitors perceived the materiality of the physical object, emphasized by virtual elements (Halskov and Dalsgaard, 2011). The Mejlby stone installation at the Kultur Historisk Museum in Randers used projections so as to narrate the story of an engraved stone. In addition to the projections audio and light in the installation room add to the dramatic effect. Animations provide data on the historical events and the carvings are depicted on the physical stone. In one of the animations, the time passing was simulated, by presenting the different environmental conditions that efface the carvings from the surface of the stone (Halskov and Dalsgaard, 2011) (Figure 57). Potential uses of projections in conservation are presented in section 4.2.2.3.

Figure 57: The Mejlby Stone (left) and the Holger the Dane (right). Installations using projections (Dalsgaard and Halskov, 2011, p. 1043-1044)

2.4 Summary

The main applications of digitization, virtual reconstruction, 3d printing and documentation, as well as the mixed reality approaches in conservation and artefacts studies presented, refer to the current state of research in the field, which has expanded with tremendous speed. We are expecting further development of methodologies and advanced operations, including documentation, dissemination and communication, preventive conservation practices, visualization and analysis. The comparison of traditional approaches and advanced technological virtual reconstruction techniques demonstrates the potential benefit for the field of cultural heritage. This is manifested by the increased cooperative projects of cultural heritage professionals and computer scientists, which are providing promising results.

Table 4 summarises the context of the present chapter, by briefly presenting the conservation problems and technological needs attributed to each one of the three basic treatment types, along with potential digital solutions. The application of digital capture techniques, virtual reconstruction and 3D printing can meet the technological needs for preventive conservation, and help conservators deal more efficiently with the preservation versus use dilemma. In addition the potential loss of evidence due to conservation/restoration operations can be minimised in case of advanced visualization and digital conservation. Moreover, although physical conservation is restricted to only one conservation strategy, resulted in one conserved object, digital conservation can simultaneously provide different versions of the conserved object by visualizing the ideal states for different points in objects life. In practical terms this can be achieved, to a certain extent, with the available computational tools, although there are still areas for improvement. Proposals exploring this are presented in Chapter 4 at a theoretical level. An evaluation of virtualization as part of the conservation process, in terms of preventive conservation and visual analysis, is presented in Chapter 5 and extended to areas of interventive treatment and restoration in Chapter 6.

Table 4: Conservation problems and technological needs attributed to the basic treatment types and potential digital solutions.

Conservation Problems	Technological Needs	Digital solutions
• mishandling	Non-contact methodologies for interaction with the archaeological material	• Digital representation • 3d digitization • Mixed reality approaches
• physical contact replication, moulding and casting	Non-contact replication techniques	• 3D digitization • Virtual reconstruction • 3D printing
• time consuming and non-safe operations (e.g. Investigative cleaning, autopsies and micro excavations)	Safe, easy, affordable and effective alternative methodologies	• 3D tomography
• time-consuming, difficult and usually unsuccessful operations (e.g. fragments identification)		• Digital refitting
• unpractical operations (e.g. extreme weight and dimensions)		• Digital representation • Virtual reconstruction
• ethical considerations (de- and re-restoration problems, previous repairs, extensive operations)		
• Potential loss of evidence (different conservation options for the various 'ideal' states of an object)		
• ethical considerations regarding the extend and the type of retouching		
• practical and ethical considerations regarding the technique, materials and extend of gap-filling		• 3D digitization • Virtual reconstruction • 3D printing of missing parts

The digital solutions presented in the present chapter overcome practical limitations of traditional approaches regarding the time and space required for their execution and safety concerns. Moreover, the virtual execution of operations respects the material integrity of the physical artefact and is in accordance with ethical considerations. This is possible using the existing technology, but the economic considerations and the access of conservation professionals to the advanced digital technologies is a barrier for their adoption. In particular, in the field of digital refitting there is still on-going work to provide a working solution to the fragments matching conservation problem. The field of restoration, due to the ethical considerations of retouching and in-painting, in addition to practical problems of the replacement of missing parts, can be benefited at a great extent, if not the most, by the application of virtual reconstruction and 3d reproduction. Nevertheless, these methodologies are not yet practiced to any great extent.

There is no doubt that the technological expertise needed, and the equipment required for the execution of such techniques, goes beyond the field of conservation as it is conceived today. Conservation nowadays is considered, generally, as an amalgam of science, art and craft. Conservation in the future should be expanded in terms of science and closer cooperation with scientific fields such as computer science and 3D graphics is expected. In that way the future conservator will be able to face the challenges of new digital techniques so as to successfully meet conservation objectives. Among all the changes introduced, the most crucial difference, from a conservator's point of view, is the virtual execution of operations. It is worth mentioning that the human-object interaction in conservation practice has decreased in the last few decades (Ashley-Smith, 2009), and has for some time been considered as a characteristic feature of the future conservator (Toracca, 1982, p.444)

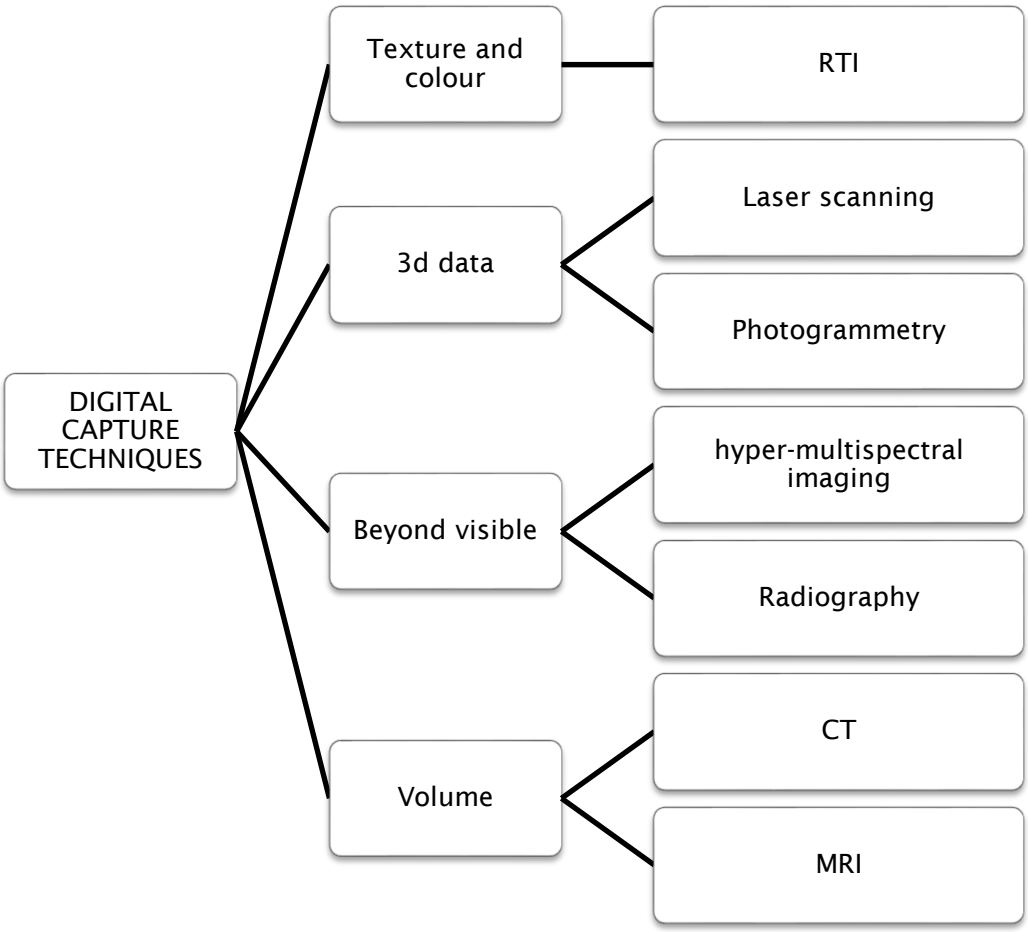
A prerequisite for virtualizing conservation is the digitization of artefacts. The analysis and categorization of the long list of digitization techniques along with applications in cultural heritage with a particular emphasis on conservation are discussed in the following chapter.

Chapter 3: Digital capture of artefacts

3.1 Introduction

This chapter is an overview of techniques for the digital capture of artefacts, which is a milestone for the concept of conservation virtualization. Although it becomes apparent from the literature review that these techniques have been applied successfully in the field of conservation and artefact studies, the vast majority of studies are published in a diverse context, and usually do not emphasise the potential for conservation practice. Nevertheless, it is crucial for conservators to be aware of the methodologies available, the nature and the abilities of the techniques, and by extension the type and quality of the visualizations produced. Also of particular interest are the issues involved in their application, and the general recommendations about each strategy based on case studies from the published bibliography, which covers a variety of material types. Apart from the straight application of digital capture (sections 3.2-3.5), synergistic approaches (section 3.6) are presented. The proposed integrative approaches demonstrate not only that research has come to a mature state of development, and is able to provide holistic approaches towards digital capture, but also the challenges of computer applications in cultural heritage.

The digital capture techniques are presented and categorised according to their ability to visualise texture and colour, features beyond the visible, volumes and 3d data (Graph 8), followed by a discussion about the application of synergistic approaches. For each category the most commonly applied techniques are discussed. For each technique the main principles are presented, as well as the necessary equipment, and a selection of case studies from the literature.



Graph 8: Digital capture techniques (Graph author's own).

3.2 Capturing texture and colour: RTI

The known visible light photographic techniques for conservation are raking, specular (axial or oblique), transmitted, dark-field and edge-illumination imaging, as well as close up photography, and photomicrography (Warda *et al.*, 2011). One of the most recent additions to this list is Reflectance Transformation Imaging (RTI). RTI (Mudge *et al.*, 2005) and the most common fitting algorithm, Polynomial Texture Mapping (PTM), developed in 2001 at Hewlett Packard Laboratories (Malzbender *et al.*, 2001), are non-destructive,

affordable and easy imaging techniques, useful for conservators, archaeologists, and curators and find specialists.

RTI is an interactive relighting technique, a synthetized image derived from a sequence of raking light images. The user can select to view the object under examination as if it was lighted from different directions, to apply digital imaging filters, to change the intensity of lights. This enables a detail examination of the surface topography and a viewing experience that fills the gap between two dimensional digital photographs and three dimensional models. During viewing the user can save two dimensional images in .jpg format (snapshots). The RTI snapshots included in this study (Chapter 5) were carefully selected so as to emphasize characteristics of the object under discussion, such as the degradation phenomena or the decorative features. In addition an attempt was made to include different rendering modes, so as to explore the advantages and limitations of each one.

Polynomial Texture Maps and Reflectance Transformation Images provide increased realism, including surface colours, self-shadowing, sub-surface scattering and inter-reflections, in comparison to bump and traditional texture mapping. Via RTI, experts and the public can experience views of the artefacts in a new way that is superior to visual examination or handling. RTI is a more holistic approach for photographic documentation than other techniques in the visible spectrum. Also, RTI advantages, as summarised by Macdonald (2011) fulfil conservation demands for efficient, affordable non-contact examination (Table 5). By extending Lehoux's (2013) point of view, that in the not-too-distant future, when RTIs will be the standard means of consulting ancient inscriptions of all sorts, one can foresee its application in artefacts of a broad variety of types and materials.

Table 5: Conservation demands for efficient, affordable non-contact examination in correlation with RTI advantages.

Conservation demands	RTI advantages
efficient examination techniques	• Higher resolution on the object surface than obtainable with 3D scanners • No data loss caused by shadows and specular highlights • Clear representation of 3D shape characteristics
limited human-object interaction	• Non-contact acquisition of data • Visualisation through interactive viewing tools
affordable examination techniques	• Simple image processing pipeline • Open source software • Affordable equipment

3.2.1 Methodology

3.2.1.1 Data capture

PTMs and RTIs can be created by the dome method (Malzbender *et al.*, 2001) or the Highlight-based method (Mudge *et al.*, 2006). The latter is able to capture data regardless of the size of the objects, without any special instrumentation. Highlight RTI captures a series of raking light images of a static object, accompanied with one or two glossy balls with a static digital camera at constant exposure. The necessary equipment includes a digital SLR camera, a tripod, a light source and a glossy sphere, whose dimension is relative to the size of the object under examination (Figure 58). The accurate execution of the procedure, as described in detail in the Guide to Highlight Image capture (Cultural Heritage Imaging, 2013c), assures the successful completion of data acquisition. The quantity of images captured varies from 40 to 80 (Earl *et al.*, 2010). However, datasets of 48 images present a minimal loss of resolution (Hamiel and Yoshida, 2012).

Figure 58: H-RTI capture (Cultural Heritage Imaging, 2013c, p.9).

The dome RTI is an automatic data capture method, which decreases time for capture - processing, and leads to better, more precise results. Various dome designs have been presented (Hewlett Packard, 2005; Malzbender *et al.*, 2006) while the design of a PTM Acquisition Device has been studied by Nemmeth (2009). The RTISAD Project has developed two domes; a larger one, 1m in diameter (Figure 59), and a portable miniature dome, 25cm in diameter (Earl *et al.*, 2011). A Mini-Dome created by the Katholieke Universiteit Leuven is suitable for small artefacts, such as cuneiform tablets, coins, textiles and paintings (Klein and Schwartz, 2010). A compromise between the highlight and the dome method is the use of rotation rings or mechanical arms for the automatic moving of light. Characteristic examples are the 'light-arm' by the National Gallery in London (Hewlett Packard, 2005) and the Quadri Flash Mantis by the Imaging Studio of the Museum Conservation Institute (MCI) (Webb and Wachowiak, 2011) (Figure 60).

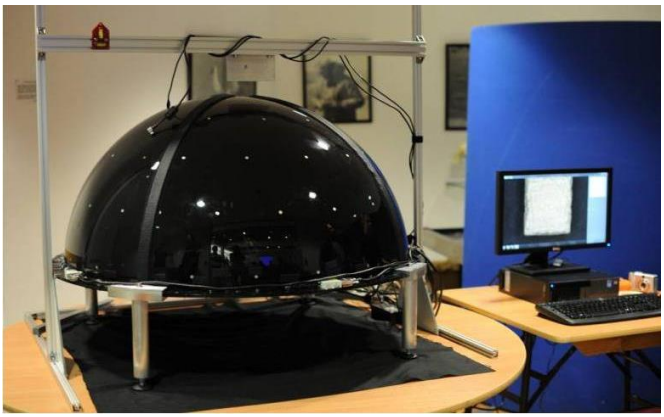


Figure 59: RTI dome, University of Southampton (Earl *et al.*, 2011, p.148).

Figure 60: QuadriFlash Mantis, Smithsonian Museum Conservation Institute (Webb and Wachowiak, 2011, p.1).

Proposals for further development of RTI data capture methodologies are presented at theoretical level in section 4.3.2.1 and at practical level in section 5.3.1.1.

3.2.1.2 Processing

The technique performs sampling and modelling of the reflectance function independently for each pixel, enabling the user to change the material properties of objects in the scene (Malzbender *et al.*, 2004). The BRDF, the Bidirectional Reflection Distribution Function describes how a material interacts with light, defines a material's property to distribute light, characterizes the colour of a surface as a function of incident light according to the direction of a viewing. Spherical harmonics (SH) and polynomial texture maps (PTM) are

used for representing BRDFs (Gunawardane *et al.*, 2009). Full spherical representation is not necessary and the use of hemispherical harmonics (HSH) is proposed (Elhabian *et al.*, 2011).

The data processing methodology uses the RTI builder software, developed by the University of Minho in collaboration with CHI in 2009. The predecessor of RTI builder was the LpTracker software, developed in 2008, which allowed the creation of LP, HLT and PTM files with a set of images. Since then the RTIBuilder software has been developed, including features for cropping, creating different size PTMs and managing the processing by implementing different operation sequences, or by reprocessing an existing dataset.

After loading the files the user can add metadata for the project, which are stored in the project log file. In the case of highlight RTI, images are loaded and saved, the sphere is selected and added by the user and then the program executes sphere and highlight detection. Finally, the PTM fitter or HSH fitter completes fitting and results in artefacts visualised in polynomial texture map or reflectance transformation imaging format (*.ptm or *.rti), using either the polynomial texture map, developed by HP researchers, or the hemispherical harmonics fitter (Mudge *et al.*, 2008), developed at the University of California, in collaboration with CHI and T. Malzbender (Figure 61). In the case of dome RTI, the builder uses a pre-built lighting position file and continues with fitting. The University of California Santa Cruz developed a specific file format for the viewing of different viewports of the same artefact. The multi-view RTI file format is actually a set of RTIs with the .mview extension[16].

[16] More details can be found in the guide to highlight image processing (Cultural Heritage Imaging, 2011).

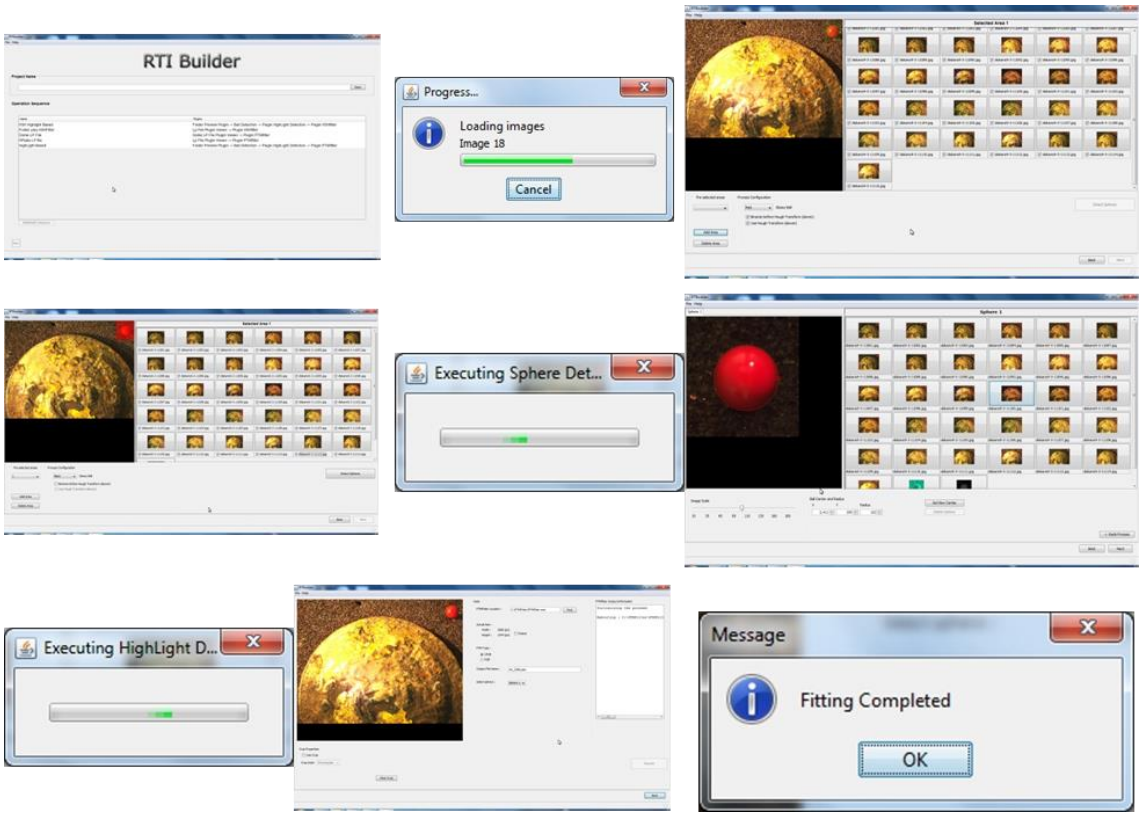


Figure 61: RTI processing with the RTI Builder, screenshots (Image author's own).

3.2.1.3 Viewing

PTM and RTI files can be viewed via specialized software. The RTI viewer (ISTI-CNR/CHI RTIViewer) (Cultural Heritage Imaging, 2013b) is compatible with both .ptm and .rti files, while the PTM viewer (HP Labs PTM Viewer) (Lyon, 2004) (Figure 62) supports only .ptm files. Both pieces of software enable interactive manipulation of the lighting position and enhancement of the final outcomes through different rendering modes. The combination of two .ptm files into one has proved to be useful for comparative study, as it enables the user to zoom simultaneously in on two .ptm files (Piquette and Macdonald, 2012).The InscriptiFact Standalone Viewer[17] developed at the University of Southern California offers similar functionality (Figure 63). A similar result, although without simultaneous zooming ability, can be acquired via digital

[17] For more details see http://ruth.usc.edu:7060/inscriptifact_standalone.html

image merging, just after data capture using the dome method and before processing.

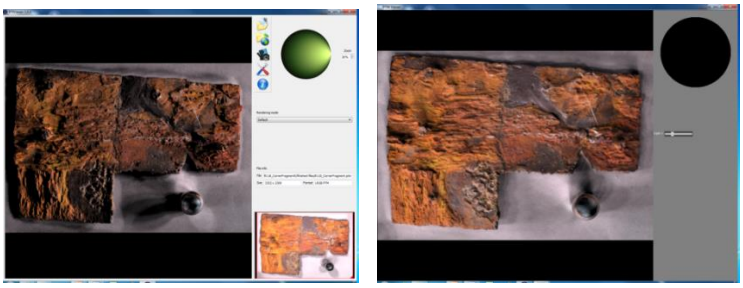


Figure 62: PTM file viewed in RTI Viewer (ISTI-CNR/CHI) (left) and PTM Viewer (HP Labs) (right) (Image author's own).

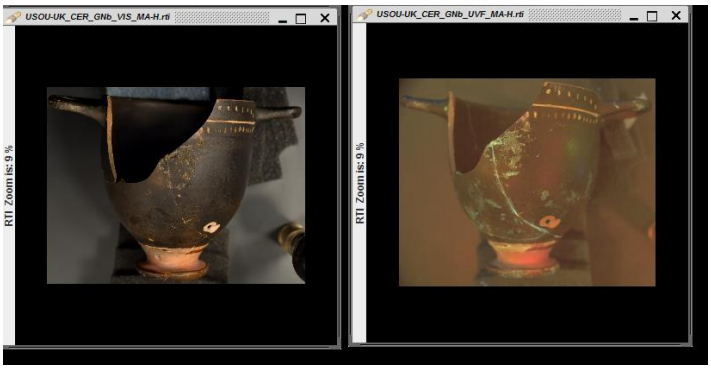


Figure 63: RTI visualization of a gnathian skyphos in visible and ultraviolet spectral area viewed in InscriptiFact Viewer (USC) (Image author's own).

Research has been directed into the development of online RTI viewers. The first online PTM viewer was presented by Clifford Lyon in 2004. Via the interactive Kiosk developed by the Visual Computing Lab of the CNR a large group of coins and medallions can be viewed online (Palma and Callieri, 2013; Palma *et al.*, 2013). Although this online viewer does not have the capabilities of the desktop viewers, such as different rendering modes or snapshot ability, it enables the easy sharing of RTI files, as well as zooming and additional information on each coin accompanied with, maps and images of archaeological sites and finds. A wordpress plugin, created by Pagi and based

on the Material Objects viewer, allows for the embedding of RTI datasets within any website (2011)[18].

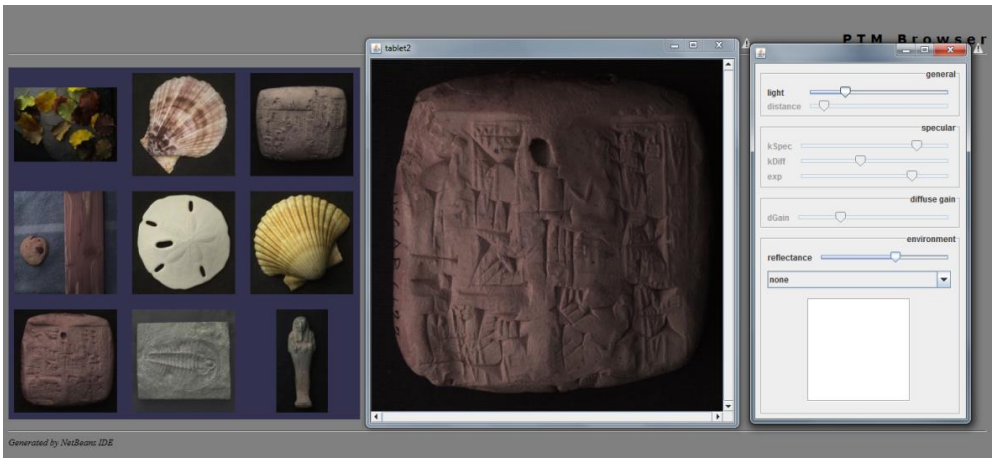


Figure 64: Online RTI visualization of a tablet. Available from: http://materialobjects.com/ptm/viewer.html

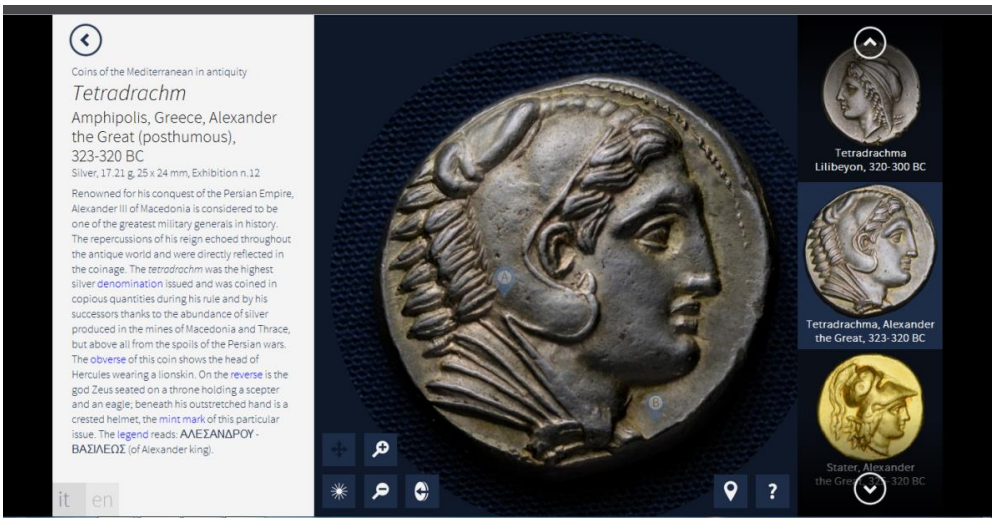


Figure 65: Online RTI visualizations of a tetradrachm from Amphipolis. Available from: http://vcg.isti.cnr.it/PalazzoBlu/

The annotations are of extreme importance for the application of RTI in artefacts examination. Annotations encourage scientific cooperation among curators, artefact specialists, archaeological scientists and conservators. Each

[18] There is on-going research by the Archaeological Computing Research Group of the University of Southampton on the development of an online RTI viewer, which combines the IIP Moo Viewer capabilities and an annotation tool.

museum professional can add annotations about material culture, archaeological provenance, interpretations of the artefacts, composition, material evidence and condition according to their expertise. The annotated RTI file is not only a record of the object, but an examination record, which can be virtually re-examined by other professionals. As such it includes the specialists' knowledge; its educational and scientific uses are extended and extra values are attributed not only to the RTI file but also to the visualised artefact.

The first step towards the development of annotated RTIs is the annotation box link, which enables the addition of textual descriptions (Earl *et al.*, 2011). The latest release of RTI Viewer software includes useful features for annotations (Figure 66). The numeric parameters values are displayed in the screen, enabling the accurate description and reproduction of a specific view of the visualised object. Each snapshot is accompanied by an XML file, where the specific numeric parameter values are displayed. The user can save the entire set of parameters that describe a specific view and add comments via the bookmarking views feature. All the data are saved in a XML file, while they remain visible in the RTI file. The bookmarks enable the use of a Highlight Box on the image, so as to highlight areas of particular interest. The whole set of bookmarks are presented in a list, enabling easy manipulation of bookmarks and associated notes (Cultural Heritage Imaging, 2013b).

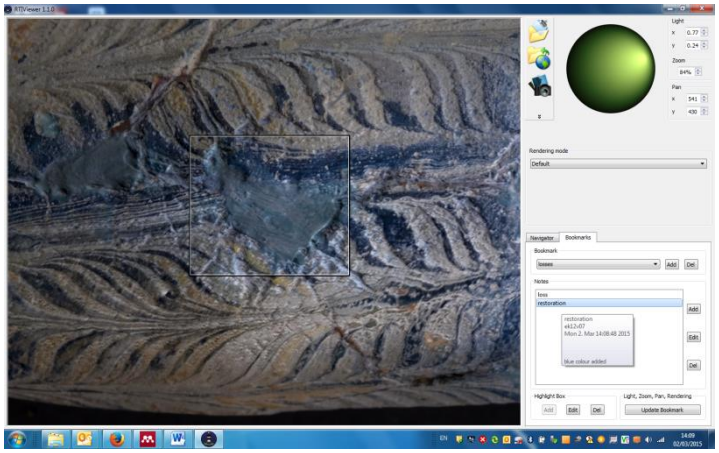


Figure 66: RTI Viewer utilising bookmarks. Area of interest emphasized using the Highlight box and explained using notes (Image author's own).

3.2.1.3.1 Rendering modes

Apart from the default the viewing software provide different rendering modes, which enable mathematical enhancement of the RTI image. The specular enhancement is the most frequently used, as it is provided by both available examples of viewing software and is also included in the latest release of the RTI Builder. Its main advantage is the improved perception of the surface shape. This is achieved because the specular enhancement algorithm separates the shape-based reflections and the diffuse RGB colour. By using the available parameters, based on the Phong reflectance model, the user can adjust the diffuse RGB colour information Kd, the shape-based reflections Ks, and the size of the area encompassed by individual specular reflections N. The main disadvantage of the specular enhancement rendering mode is the false visualization of colour information (Cultural Heritage Imaging, 2013b). The diffuse gain rendering mode exaggerates the surface texture by increasing the height and depth changes. In that way it enhances the perception of surface shape features, but simultaneously introduces changes in the RGB colour representation. The value of the diffuse gain can be adjusted using the gain parameter (Cultural Heritage Imaging, 2013b). In RTI the sharpening rendering modes apply an unsharp mask to the normal data, so as to detect and underline variation in texture and colour. The image unsharp masking mode results in an edge contrast effect, by applying a mask to the image colour data. The normal unsharp masking exaggerates surface contrast by masking the normal image and colour data. The luminance unsharp masking emphasizes depth discontinuities while the coefficient unsharp masking underlines reflectivity discontinuities (Cultural Heritage Imaging, 2013b). The goal of the multi-light enhancement modes, available in static and dynamic mode, is to create a more complete rich of detail visualization, avoiding areas of deep shadows and little or no detail, even in low angles. The algorithm divides the image into tiles, and for each of them chooses light direction in accordance with the chosen energy function, relevant to the neighbouring light direction (Cultural Heritage Imaging, 2013b).

3.2.2 Applications

Previous work has already proved that RTI significantly contributes to analysis, conservation and representation (Earl *et al*., 2010). There are many interesting applications in the field of cultural heritage, based on its ability to acquire and represent the 3D reflectance properties of objects. Related projects are the Antikythera Mechanism (Freeth *et al*., 2006), the RTISAD Project of the University of Southampton and the University of Oxford (Earl *et al*., 2011) and RTI in art conservation, a collaboration between the Fine Arts Museums of San Francisco and Cultural Heritage Imaging (CHI).

The technique has found applications in a broad range of material and artefacts types, including epigraphy and study of ancient documentary artefacts (Earl *et al*., 2011), incisions in bone (Purdy *et al*., 2011), stone (Piquette, 2011; Gabov and Bevan, 2011), rock art (Duffy *et al*., 2010; Mudge *et al*., 2006), statues (Earl *et al*., 2009), wood (Karsten and Earl, 2010) and fossils (Hammer *et al*., 2002) (Figure 67). The size of the objects under examination is irrelevant, and varies from large objects (Corsini *et al*., 2006) to microscopic features (Kotoula, 2013).

Figure 67: Detail, decorated side of the Hunters Palette (EA 20792, British Museum) showing evidence for re-carving (Piquette, 2011, p. 18).

RTI is considered to be a powerful documentation tool for numismatic studies. It is a valuable tool for coins identification, regarding problems of small size, low relief detail and material preservation. Previous work in the field of RTI in numismatic studies demonstrated advantages in identification and documentation issues in comparison to traditional approaches, as well as

improved communication and dissemination abilities (Mudge *et al.*, 2005) (Figure 68). Since then the application of RTI has been applied to coins dated back from ancient to Byzantine times (Goskar and Earl, 2010; Palma and Callieri, 2013)

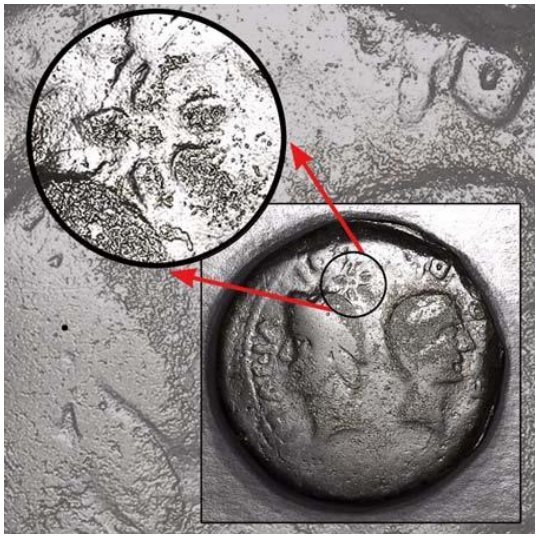


Figure 68: RTI image of the Julian Star coin (Mudge *et al.*, 2005, p. 36).

The application of PTM in the National Gallery proved that the technique provides detailed visual representations of the paintings and mock ups and enables researchers to detect and display features related to materials and techniques employed by the artists, such as brush strokes, signatures, wood grain, pentimenti as well as damage, such as craquelure, cracks, general and point surface deformations-distortions (Padfield *et al.*, 2005). RTI was employed in the study of Henry O. Tanner paintings (Baade *et al.*, 2012), Lovis Corinth and the Adoration of the Shepherds by Domenico Beccafumi (1545-50) (Castriota and Serotta, 2011). Also, RTI revealed the relief lines and dots, characteristic feature of the red figure technique, and enabled researchers of the Worcester Art Museum to reach conclusions about the tool used during the decorative process (Artal-Isbrand *et al.*, 2011) (Figure 69-70).

Figure 69: RTI of painting showing normal lighting (left) and specular enhancement (right) (Wachowiak and Webb, 2010, p. 17).

Figure 70: RTI Detail of a red-figure Attic vase from the Worcester Art Museum (Artal-Isbrand *et al.*, 2011).

Proposals for further development of RTI and application in a broad variety of artefact and material types can be found in be found in sections 4.3.2. The proposed methods are presented in section 5.3.1 trialed in section 5.3.2 and evaluated in section 5.5 leading to conclusions regarding the contribution of RTI in conservation practice in section 5.6.1.

3.3 Capturing beyond visible

3.3.1 Hyper-multispectral Imaging

Areas of the electromagnetic spectrum, which are not visible to the human eye, i.e. the infrared and the ultraviolet, have been used for the examination of artworks and antiquities.

Infrared imaging provides information about layering of painted artefacts and works of art, epigraphy on textile, wood, stone, metals, and ceramics. It penetrates aged and/or oxidised varnishes and colour layers. It reveals stages of the creation of an artefact, details hidden beneath coloured varnishes or degradation effects, such as encrustations. It is extremely helpful for the detection of “pentimenti”, under-drawings and over-paintings (older or modern). Also, it assists identification and differentiation of materials. It is used in authenticity studies and condition reports. The vast majority of publications relevant to multispectral imaging, and in particular in the IR region of spectra, are dealing with painted works of art, canvas paintings and painted wood panels, as well as with documentary artefacts.

Ultraviolet imaging provides an easy way to characterize materials and examine surfaces. Not only the presence of surface coating, over-paintings and other modern additions can be determined, but also the conservation state of these can be examined and recorded. Flaking losses and abrasions of an invisible transparent varnish, modern repairs, and techniques of manufacture/application of materials can also be easily investigated (Warda *et al.*, 2011). Verhoeven and Schmitt (2010) refer to applications of NUV in the study of documentary artefacts, faded inks, pigments, ceramics, tapestries, textiles, paintings and sculptures.

3.3.1.1 Methodology

3.3.1.1.1 Equipment

Infrared imagers can be used for more specialised applications as their sensitivity range is from 950nm to 2500nm. Modified DSLR cameras (Digital single-lens reflex) and digital cameras with CCD (charge-coupled device) and CMOS (complementary metal-oxide semiconductor) image sensors have a sensitivity from 350nm up to 1000nm, covering the near infrared region of interest for conservation and artefacts studies . Multispectral imaging with digital cameras requires the attachment of filters (Warda *et al.*, 2011). For infrared, imaging filters that absorb visible and transmit infrared are used. There is a long list of filters of that type, which transmit longer or shorter wavelengths in the infrared region, from 720nm to 1000nm. For ultraviolet imaging UV transmitter filters are necessary. Other filters and combinations can be employed in specialised set-ups of multispectral imaging. The choice of filter depends on the characteristics of the artefacts and the scope of the multispectral examination. The most easy and safe lighting options with better performance is the use of IR and UV LED lights.

3.3.1.1.2 Set-up

The most common techniques are the reflected UV and IR imaging. The transmitted IR imaging technique is useful in case of translucent materials, canvas paintings, mounded papyri, photographic material, and works of art on paper or archival material, because it eliminates reflections from the outer surface, leading to enhanced results (Gavrilov *et al.*, 2008). Transmitted imaging (TI) techniques, proposed for the first time in the 1970s (Cornelius, 1977) and further developed during the 1980s (Kushel, 1985), are considered as standard photographic techniques for the examination of artworks. In TI the camera records the radiation transmitted through the surface under investigation. Trans illumination and irradiation is useful for the examination of the painting history of works of art, and for condition reporting. Notable is the efficiency of TI in providing evidence for craqueleure. Moreover, TI differentiated successfully the painting techniques applied as well as the variable thickness of the painted layers in the different areas of painted surfaces (Cucci *et al.*, 2012) (Figure 71).

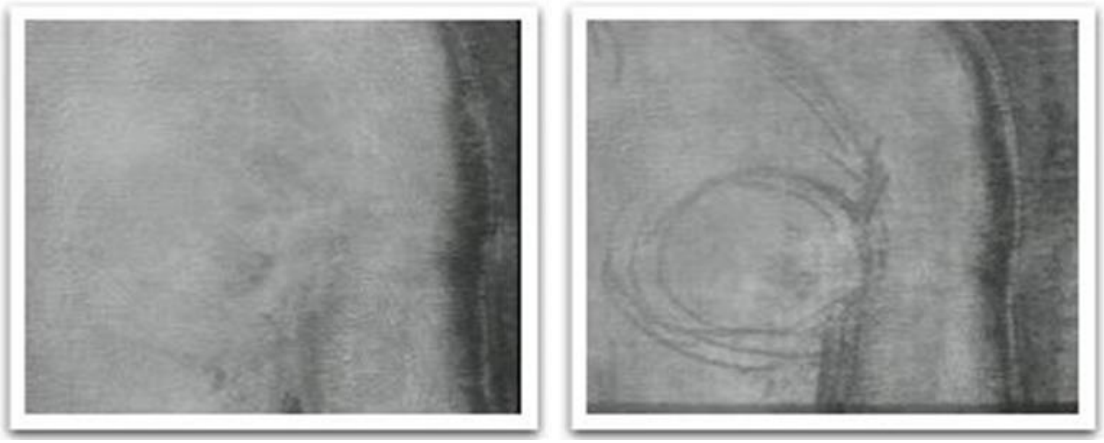
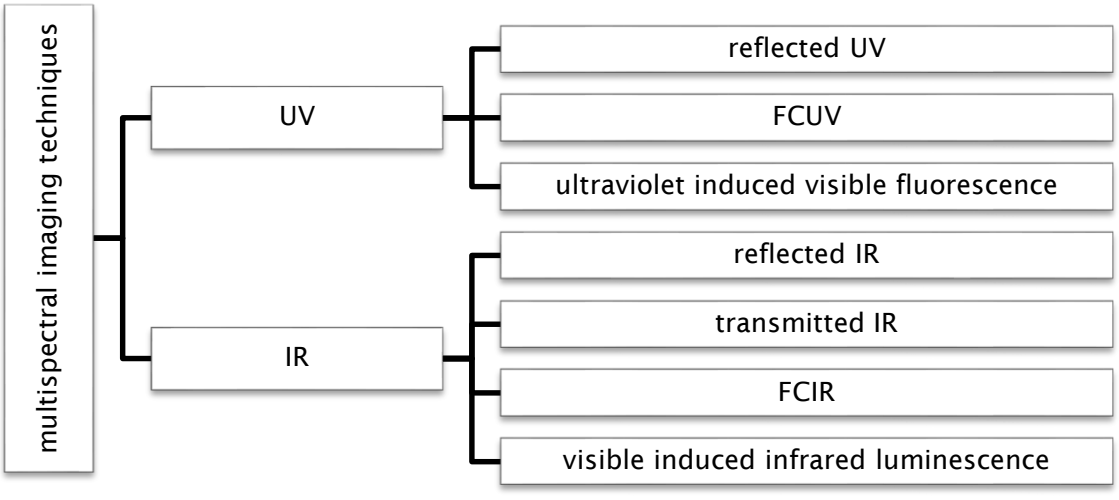


Figure 71: Detail of Psyche by G. F. Watts. IR Reflected (left) and transmitted (right) (Moutsatsou *et al.*, 2011, p.57).

Visible induced infrared luminescence and ultraviolet induced visible fluorescence imaging are other set-ups used for specialised applications. The less common technique for multispectral examination is the photo-induced fluorescence digital imaging. Among this group of techniques, best known for the study of painted surfaces, binders and varnishes is the ultraviolet (UV)-induced fluorescence imaging in the visible (VIS) range, rather than the VIS-induced fluorescence imaging (Graph 9).



Graph 9: Spectral imaging techniques (Graph author's own).

3.3.1.1.3 Processing multispectral images

Further processing of spectral images presents interesting applications for cultural heritage, such as the false colour IR and UV imaging. False Colour IR (FCIR) technique combines visible RGB colour and infrared imaging. It is based on the different response of materials to infrared radiation. It employs a simple processing pipeline, which includes the substitution of the red channel in the RGB image by the IR, the green by the red, and the blue by the green. The UV analogue is the False Colour reflected UV (FCUV), presented by Aldrovandi in 2005. It uses a technique similar to the FCIR channel substitution schema. FCIR and FCUV (Alexopoulou *et al.*, 2013; Buoso *et al.*, 2009; Hoenige, 1991; Knox *et al.*, 1997; Moon *et al.*, 1992; Warda *et al.*, 2011) have been used for materials differentiation and characterization, especially for painted works of art and pigments research (Figure 72).

Figure 72: Visible, Infrared and FCIR image of painting, Perugino, Chapel of Saint Severo, 1520, Perugia, Italy (Douma, 2008).

3.3.1.2 Applications

3.3.1.2.1 Painted surfaces

Near infrared bands are particularly useful for damage assessment and for revealing the under drawings (preparatory sketch) beneath the paint layers and for the determination of painting techniques for the sketch, enabling authentication purposes and art history studies (Liang, 2011). Original features

covered by restorations and delamination can be observed (Gavrilov *et al.*, 2008), characterization and mapping of pigments and inks is possible, and the study and differentiation of organic binding media in cases of multispectral imaging of painted artefacts and drawings can also be determined (Fischer and Kakoulli, 2006) (Figure 73). A characteristic example is the application of multispectral imaging in mural fragments from the Late Classic Maya civilization, which provides an insight into Mayan painting techniques and enhancement of details, offering also the opportunity for virtual decolouring of colour layers based on the different response of pigments in different ranges of spectrum enables (Kamal *et al.*, 1999). In canvas paintings the most appropriate method is the transmitted IR and NIR imaging (Moutsatsou *et al.*, 2011).

Figure 73: Infrared image showing the pentimenti of the hand (Fischer and Kakoulli, 2006, p. 6).

The vast majority of published research in ultraviolet imaging refers to paintings. This is reasonable because of the ability of UV to identify retouching-over painting (Daniilia *et al.*, 2008, Lahlil and Martin, 2012; Stratis *et al.*, 2013; Webber, 2008). Moreover, ultraviolet imaging can be of great assistance in studies of varnishes, because of the range of responses of

different types of varnish to UV radiation. Old natural resin varnishes fluoresce unlike newer ones, providing a tool for material differentiation, even if their optical properties under visible light are similar (Figure 74). Townsend (2010) discusses the evidence for varnishes using ultraviolet imaging techniques. From the close examination in ultraviolet of the cross sections of paintings of British artists from the nineteenth century in the Tate, the original varnish and the historical treatment, including selective varnish cleaning and over painting, were detected (Townsend, 2010).

Figure 74: Visible (top) and UV fluorescence (below) image of an icon (Maino, 2007, p. 4).

The visible induced infrared luminescence is useful for the examination of documents and characterization of pigments, such as cadmium pigments, yellow and madder lake and Egyptian blue. Verri (2009) proposed this technique for the mapping of Egyptian blue, Han blue and Han purple pigments. It is also possible to differentiate other pigments with similar reflective properties in the visible spectrum, such as Egyptian blue and Egyptian green (Verri *et al.*, 2009). The application of ultraviolet-induced visible fluorescence imaging in commonly found materials in museum collections has been discussed in the literature (Grant, 2000) (Figure 75).

Figure 75: Visible (top) and visible induced infrared luminescence (below) image of a mummy cartonnage. Identification of Egyptian blue. Available from: http://www.penn.museum/sites/artifactlab

Proposed developments of infrared RTI and PG for the study of paintings are presented in sections 5.3.2.1 and 5.4.2.1 respectively.

3.3.1.2.2 Inscriptions

Multispectral imaging has been used to document and improve the reading of ancient inscriptions, as demonstrated by numerous successful applications, including papyri (Alexopoulou *et al.*, 2013), Dead Sea Scrolls (Knox *et al.*, 1997) (Figure 76), palimpsests (Easton *et al.*, 2003) and ink-written texts on pottery fragments (Faigenbaum *et al.*, 2012). Multispectral imaging enhances the legibility of faded texts, even in cases of charred and partially burnt artefacts. It has been reported that UV imaging gave the best results of a range of multispectral imaging techniques applied on a damaged medieval manuscript (Montani *et al.*, 2012) (Figure 77). It is reasonable that Goltz (2012), in his review paper for the instrumental study of historical inks, refers to the use of multispectral and hyper spectral imaging for the assessment of inks in historical documents.

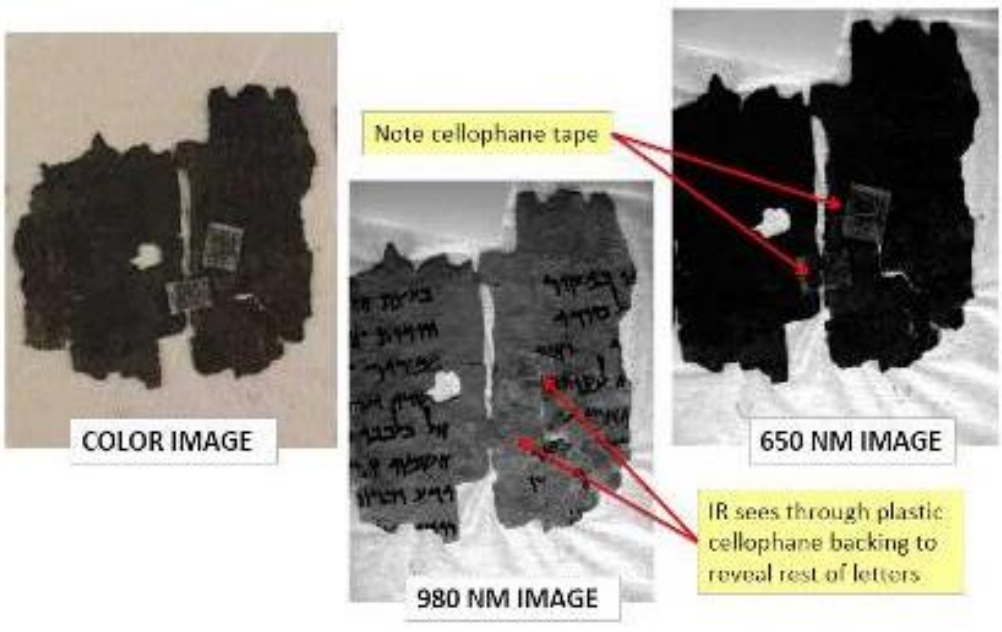


Figure 76: UV-VIS-IR images the Dead Sea Scrolls from Israel captured by Dr. Greg Bearman. Available from: http://www.jenoptik-inc.com

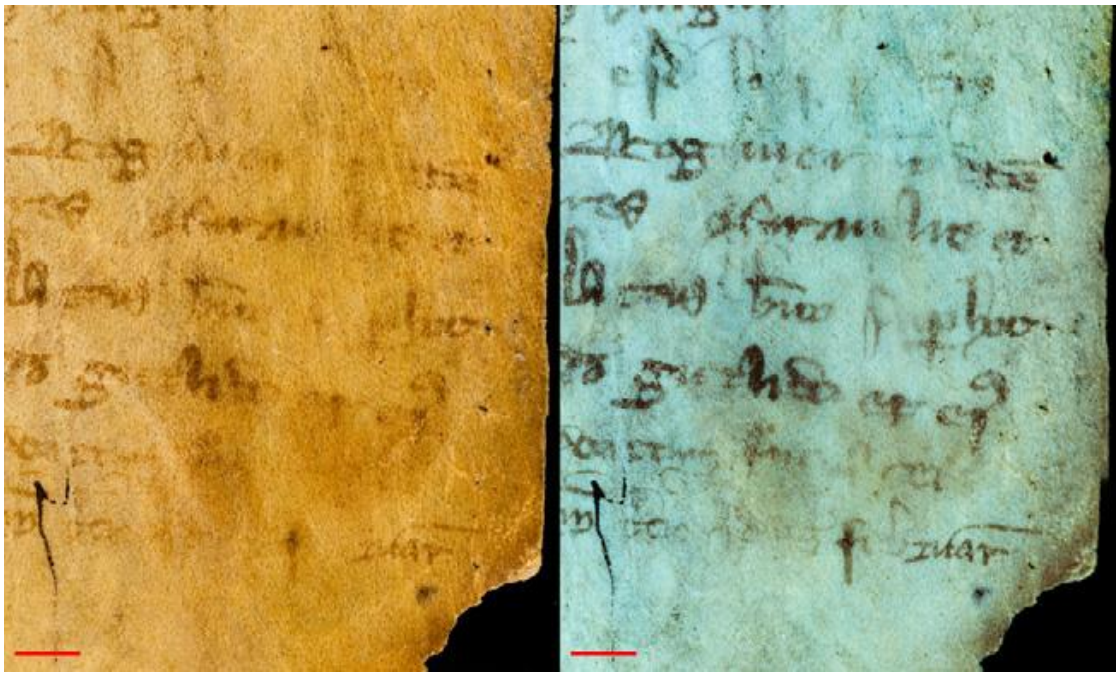


Figure 77: Damaged medieval manuscript, detail. Visible (left) and UV (right) image (Montani *et al.*, 2012, p. 228).

Apart from the improved readability the material differentiation is of great importance for the study and conservation of ancient documents. For example, in the case of the Egyptian papyrus from the collection of the Brooklyn Museum, the carbon black text absorbs infrared radiation and appears intense. However, in contrast, the iron oxide red pigment is faded due to the low absorption of iron in the infrared spectral region (Kapetanakis, 2010) (Figure 78). The different response of materials to radiation can differentiate texts written in different historical periods (Maino, 2007). A characteristic example is the Archimedes Palimpsest (Easton *et al.*, 2003) and the multispectral examination of an 11th century AD palimpsest (Balas *et al.*, 2003). Of particular interest for conservation is the differentiation of ink and damage by means of multispectral and false colour imaging, especially under near infrared radiation, which was reported in the case of highly deteriorated and fragile papyrus fragments (Alexopoulou *et al.*, 2013).

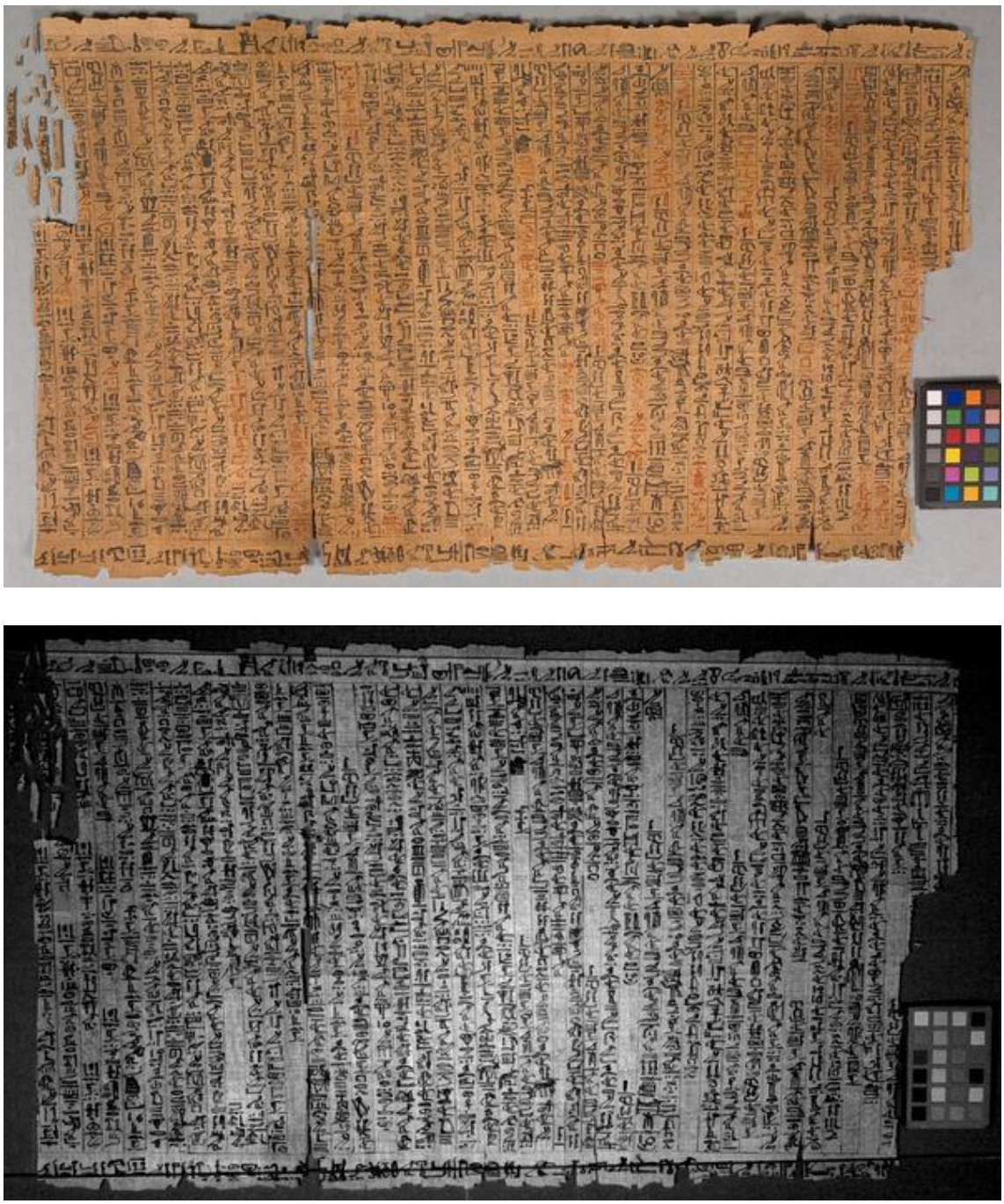


Figure 78: Fragment from the Book of the Dead of the Goldworker of Amun, Sobekmose. New Kingdom, Dynasty 18, ca. 1479-1400 B.C.E. Brooklyn Museum. Visible (top) and IR (below) image (Kapetanakis, 2010).

Proposed developments of infrared RTI for the study of documentary artefacts are presented in section 5.3.2.2.5, demonstrated by the Derveni Papyrus RTI case study.

3.3.1.2.3 Ceramics, glass and organics

Although paintings and documentary artefacts are more often examined by means of multispectral imaging, the contribution in non-destructive examination of other material types is notable, because of the ability of IR to penetrate saline encrustations, resinous crusts and other forms of patina found on pottery and glass. Ultraviolet spectral light can assist the examination of organic materials, such as textiles. Taking into consideration that UV fluorescence diminishes with age, an initial comparative dating is possible. Also, untreated fibres can be identified (Marsh, 1978).

In the case of chemically treated, painted or dyed textiles ultraviolet radiation can assist the examination of pigments and dyes applied. A well-known example of multispectral imaging in textiles is the Turin shroud. Researchers have been lead to the conclusion that the different colours of yarn are best observed in ultraviolet photographs. Another interesting outcome of the ultraviolet examination of the shroud is the definite rejection of the hypothesis that the hair left an image on the material, based on the absence of fluorescence in the area near the hair (Fanti *et al.*, 2005).

Proposed developments of infrared RTI and PG for the study of ceramics are presented in sections 5.3.2.2.4 and 5.4.2.2.1 respectively.

3.3.1.2.4 Conservation assessment

Spectral imaging has been used in order to capture and visualize features which are invisible to the naked eye, such as the detection of damage, past intervention and retouches. Ultraviolet can document restoration, such as repairs and joins in ceramics, even in the case of fully imitative restoration approaches. Although the latter is not advisable, according to restoration ethics, it was a common practice in the past; as a result it is particularly useful for the assessment of previous undocumented repairs (Figure 79).

Also, it can provide a valuable tool in the assessment of conservation treatments. Multispectral imaging can assist conservation examination and monitoring as minor colour differences can be detected. Alterations introduced during conservation operations or damage can be determined and visualised, providing a better understanding of the material ageing phenomena, as well as

for the processes used in order to pace their rate, as demonstrated by applications on marble, paper, parchment and wall paintings (Liang, 2011). A characteristic example is the experimentation on an old manuscript, cleaned by laser, which pointed out that at 380nm the cleaning process can be examined and the alterations introduced in the material, beyond the visible, can be visualised (Balas *et al.*, 2003).

Figure 79: Visible and UV image of an Islamic bowl from the Metropolitan Museum (Parry, 2013).

3.3.1.2.5 Revealing manufacture evidence

Other issues of crucial importance, such as construction techniques, can be examined via spectral examination. Verhoeven (2008) provides examples of NIR images of ceramics with paints and inks. Moreover, this work shows that infrared imaging can show the areas more exposed to reduction during the firing process, or due to the incineration of organic material and/or decomposition of calcite inclusions, which appear differentiated in comparison to the visible image (Verhoeven, 2008) (Figure 80). Also worthy of mention are UV applications in authenticity and bio-deterioration studies. Authentication studies for stone, alabaster, bone and ivory artefacts can be assisted by UV imaging because of the difference in the response of newly cut and old material (Marsh, 1978).

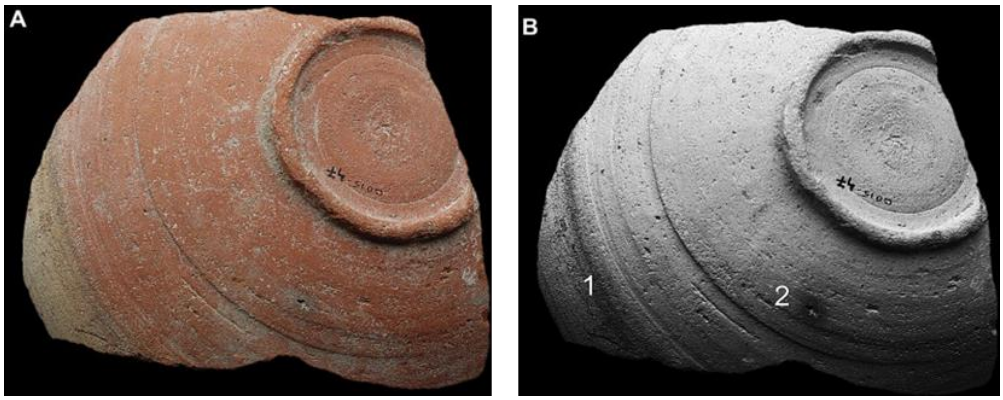


Figure 80: Visible and Infrared image of a North African Late Punic/Early Roman bowl. (1) and (2) indicate zones of increased reduction (Verhoeven, 2008, p.3097).

3.3.1.2.6 Multispectral imaging and instrumental analysis

Baldia and Jakes (2007) reasonably propose the application of multispectral imaging techniques prior to sampling for destructive physicochemical analyses, in order to select samples of different chemical compositions. They presented as an example a degraded turquoise colorant on textile, but the same approach can be similarly useful in the case of leather or wood painted artefacts. Similarly, microscopic ultraviolet examination assisted the selection of the samples for XRF analysis of fifteenth- and sixteenth-century Italian drawings in the Metropolitan Museum of Art (Dahm, 2010). This effective examination methodology can assure better results, providing an enhanced sampling strategy.

3.3.1.3 Terahertz Imaging

THz radiation penetrates nonpolar and nonmetallic materials, such as organic, plastics and ceramics, and visualizes hidden features. Among its stronger advantages is the lack of irradiation risks. It is less explored than other spectral bands and THz technology is less advanced, including materials, detectors and sources. This phenomenon is described as the '*THz gap'*. (Lee, 2009, Kawase *et al.*, 2010). Nevertheless, THz imaging has attracted recently a lot of attention, mainly as a technique complementary to CT. For example it has been used for the study of a mummified ancient Egyptian hand (Öhrström

et al., 2010), for the characterization of the stratigraphy of corrosion layers in copper alloy artefacts (Jackson *et al.*, 2014), for the analysis of pigments and painted surfaces (Fukunaga *et al.*, 2009), architectural parts, such as wall fragments (Walker *et al.*, 2013), pottery (Bessou *et al.*, 2012; Caumes *et al.*, 2011) (Figure 81) and inks (Abraham *et al.*, 2009) (Figure 82).

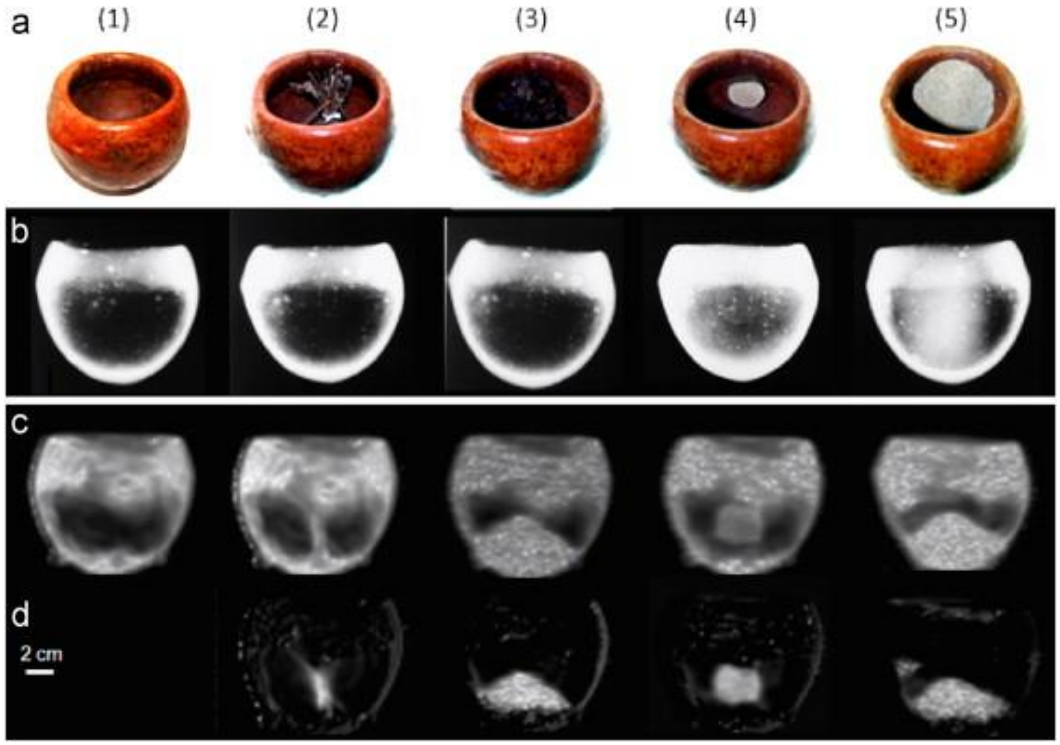


Figure 81: (a) Photographs of model objects. (b) Radiographs. (c) THz imaging. (d) Differential THz imaging (subtraction image between filled jar and empty one). (1) Empty pot, (2) pot with dried flowers, (3) pot with pine bark, (4) pot with hazel wood slice (11 mm thick), and (5) pot with white sand (Bessou *et al.*, 2012, p. 4178).

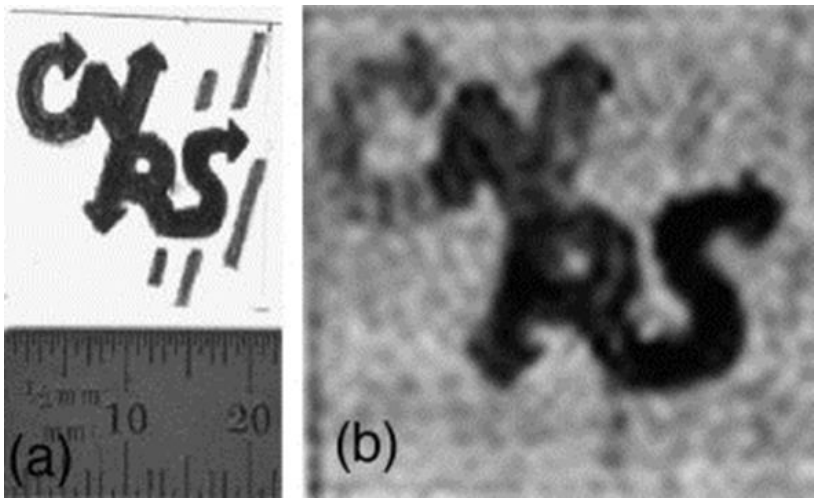


Figure 82: Digital photograph (a) and THz image (b) of logo drawn with five different graphite pencil grades. Oblique lines around S: HB, C: 2B, N: 4B, R: 6B, S: 8B (Abraham *et al.*, 2009, p. 3106).

3.3.1.4 Advantages and disadvantages

The advantages of multispectral imaging techniques for artefacts diagnostic examinations are the following:

- they reveal significant information for condition reporting and manufacture
- they assist material characterization and differentiation
- they can be applied to a broad range of material and artefact types
- there are no size constrains, although microscopic hyper-multispectral techniques are not very common
- in situ capture is possible, with easily transportable equipment, although within the museum environment data capture is easier and more practical and efficient due to the controlled environment and lighting
- the computational and equipment cost is relatively low compared to other non-destructive testing techniques
- the level of expertise required is relatively low compared to other non-destructive testing techniques and museum professionals are familiar with this kind of examination

A critical aspect for the application of hyper-multispectral imaging in cultural heritage is that radiation is an agent of deterioration for antiquities and works of art, which causes colour and strength change to organic materials, such as paper, cotton, linen, wood, parchment, leather, silk, wool, feathers, hair, oils, glues, gums, resins, plastics and dyes (Thomson, 1994). Physical processes, such as oxidation, cross linking, breaking of chemical bonds and colour changes occur due to the electronic excitation of materials by visible and UV radiation (Ginell, 1994). Shortwave UV plays a more significant role than visible and IR radiation for the physicochemical degradation of archaeological materials by initiating oxidative reactions, depending on the materials' composition and temperature and the presence of other substances (Goffer, 1979). But for the more sensitive materials the reduction of visible radiation is also important, as both UV and visible radiation can cause damage (Thomson, 1994). Infrared radiation causes molecular vibrational and rotational excitation and is responsible for a rise in temperature (Ginell, 1994), which increases the rate of deterioration as well as other physical properties, such as age embrittlement. Also, it causes expansion, favours biological activity, and above all leads to drying (Thomson, 1994). Brill discusses the mechanical damage, such as shrinkage, wrapping, peeling and cracking, due to infrared radiation in case of wood, glass, ceramics and wax objects, as well as in ivory, paper, parchment, leather and textiles (Brill, 1980). Appropriate lighting is a necessity for the safe hyper-multispectral examination of artefacts. LEDs are considered to be the most convenient and safe choice (Ishii *et al.*, 2008), which have found application in museums beyond simple illumination of artefacts (Viénot *et al.*, 2011). Photodegradation is a popular and timely research topic (see for example Macchia *et al.*, 2013; Bussiere *et al.*, 2014), but it will not be examined further because it goes beyond the scope of the present study.

In order to perform an advanced technical examination of the inner morphology of artworks hyper-multispectral imaging should be combined with other non-destructive testing techniques, the most common being radiographic examination, which will be discussed in the following section.

Application of multispectral imaging and novel IR and UV visualization methodologies can be found in Chapter 5.

3.3.2 Radiography

X, neutron and gamma radiography are considered complementary techniques, although gamma rays have significant disadvantages and so their use in cultural heritage is limited. Owing to that, for the purposes of the present study, x-radiography and neutron radiography will be discussed.

3.3.2.1 From conventional to digital radiography

Radiography provides an insight into the internal structure of objects and has found many applications in cultural heritage. Nowadays digital detectors and radiographic film are both in use. A standard image capture method in archaeology is the production of conventional film radiographs, because they are not costly and many research institutions already possess the conventional radiographic equipment. The cost of digital systems is still high, while the image quality of budget systems does not meet the needs of archaeological applications (English Heritage, 2006). In the future digital radiography will become the common practice for archaeological archives. Until then digitization of film radiographs have been proposed and practiced by many institutions (O'Connor and Maher, 2001).

3.3.2.2 X radiography (XR)

XR visualises the internal structure of objects due to its ability to show density variations, assisting condition reporting and revealing manufacture evidence as well as ancient and modern repairs. It has been used for coins identification, determination of corrosion state (Bork, 2011; Goodburn-Brown and Jones, 1998) and the study of ceramics (Berg, 2011) including complex projects, dealing with wall thickness and porosity distribution (Pierret *et al.*, 1996), as well as a great variety of artefact types, such as painted artefacts and icons (Lahlil and Martin, 2012), mummified corpses, such as the iceman (Gostner *et al.*, 2011) and organic materials (Yoder, 2013), bone and composite objects in order to define manufacture techniques and repairs. The contribution of XR in the study of ancient metal working techniques is notable, as it reveals details about casting (Scott and Dodd, 2002) and fusion techniques, enabled the detection of material differentiation and hidden fractures (Franceschi *et al.*, 2004). In the case of highly corroded, even completely mineralised, metal

objects the information obtained provides a long-term visual record which is not comparable to other techniques for identification, classification and dating (Figure 83).

English Heritage (2006) summarises the benefits of XR as follows:

- visual record of shape, technology and condition
- aid to identification
- non-interventive
- non-destructive
- cost-effective
- long-term record of deteriorating objects

Nevertheless XR of gold, silver and lead has some drawbacks, because these metals appear nearly opaque to X-rays. In case of materials that are not well addressed by x-radiography, neutron radiography can be used as a complementary technique for the investigation of internal structure of objects.

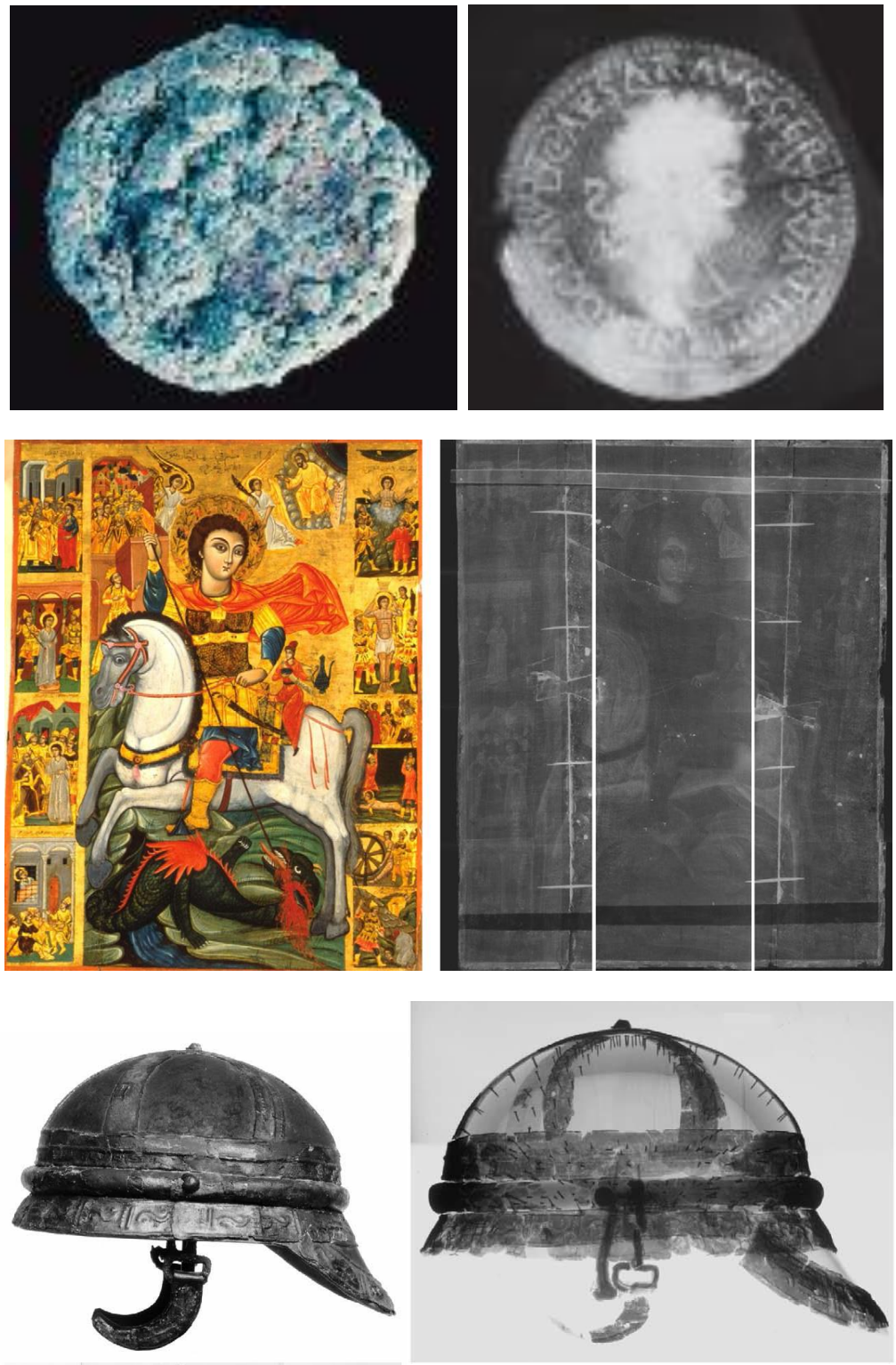


Figure 83: Digital images (left) and x-radiographs (right). Roman coin (top) (English Heritage, 2006, p. 3), icon (middle) (Lahlil and Martin, 2012, p. 335) and helmet (below) (Lehmann *et al.*, 2005, p. 73).

3.3.2.3 Neutron radiography (NR)

During the last few decades there have been an increased number of NR applications (Figure 84) for the detection of hydrogen like organic materials, corrosion products and metals, in particular heavy metal lead. The sensitivity of NR in the detection of hydrogenous materials such as water, water-logged ceramics, organic materials such as wood or water-logged wood, plants, seeds, food remnants, leather, textiles, paper, fragrances, tar, and resins is remarkable. In addition the transparency of technical metals such as copper, tin, iron, bronze, lead as well as rock materials, minerals and glass, ceramics should be noted. Making use of the above characteristics, NR has been used to uncover fine structures inside thick metal layers and for the detection of materials of organic nature hidden inside metals (Rant *et al.*, 2006). This provides an insight into manufacture, condition reporting, and conservation and authenticity studies. A characteristic example is the exploration of the manufacture techniques of a bronze head found in Switzerland. The determination of two stages of production, primary, the metal casting and, secondary, the filling with lead, would be impossible using other means of investigation (Lehmann, 2006). In the presence of heavy metals, Pb, Sn, Cu on thick objects along with corrosion layers, as well as organic materials, such as resins, adhesives and lacquers, NR and neutron tomography is proposed. But when Co or Ag is present, neutron analysis should be avoided due to radio activation of the object (Lehmann *et al.*, 2010) (Figure 85-86).

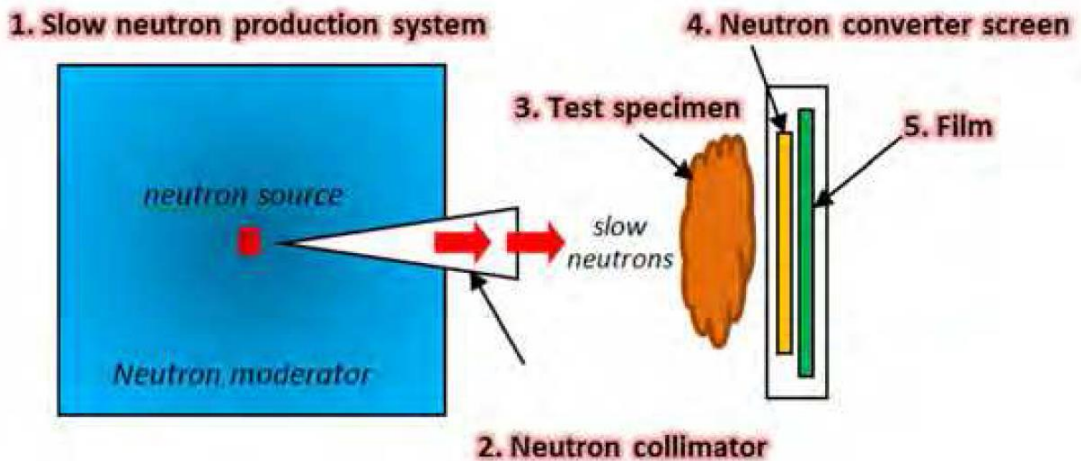


Figure 84: A typical neutron radiography system (Chankow, 1990, p. 74).

Figure 85: Roman hanging bronze lamp, digital image (top) and neutron radiograph (below) showing inside residue (Ryzewski *et al.*, 2013, pp. 348-349).

Figure 86: Neutron radiograph of the helmet in Figure 83 (Lehmann *et al.*, 2005).

Characteristic of NR's potential for conservation is the examination of conservation operations in stone, particularly sandstone and limestone samples, in order to explore the penetration of consolidants and water repellents. The visualisation of the penetration depth of the organic conservation products enabled the assessment of the conservation operations efficiency (Cnudde *et al*., 2007). In a recent, similar project, the application of 10% Paraloid® B-72 in acetone by brushing and immersion was tested on two ancient ceramic tiles, reaching the conclusion that the former method is more efficient (Prudêncio *et al*., 2012). The ability of neutrons imaging to visualise the penetration and distribution of organic conservation products inside archaeological materials can be used as a tool for the improvement of conservation techniques.

3.4 Capturing volume

Radiography made possible the imaging of internal features of objects, however one of its significant limitations is that three-dimensional inner structures of the objects are represented by two-dimensional images. Another disadvantage is that the superimposition of structures leads to poor contrast. In that way important evidence for the complete investigation of the object remains unrevealed. CT, which is the mathematical reconstruction of three-dimensional images from x-ray pictures, overcomes these limitations of X-radiography and provides a much better overall examination and visualization of the object. In CT scans the contrast in the image is greatly improved and depth information is provided by three dimensional models (Michael, 2001). Similarly, Magnetic Resonance Imaging (MRI) overcomes the limitations of the NR.

3.4.1 Computed tomography (CT)

CT was introduced in the late 1960s / early 1970s, rooted in experiments on medical radiological applications. It was a revolutionary diagnostic technique which found tremendous appreciation by the international medical community. The first industrial and research application was conducted during the 1970s, but it was not until the 1980s that the technique was used in cultural heritage (Reimers and Riederer, 1984).

3.4.1.1 Instrumentation

The CT scanning systems used in the early 1970s, referred to as first generation, were really slow because they had a single detector and employed translate and rotate motions. In 1974 the second generation CT scanners were less time demanding because of the fan-beam of x-rays and the small number of detectors which simultaneously capture multiple projections. Third generation scanners, installed in late 1975, equipped with 1000 individual detectors, which rotate along with the x-ray tube, were wide enough to make translation unnecessary. This CT proved highly successful and still remains the basic configurement. By 1976 fourth generation scanners employed 5000 individual detectors around the object to be scanned and the only rotational component is the x-ray tube. The fifth generation involved magnetic fields instead of mechanical motion enabling faster data acquisition. An alternate CT strategy, which became popular by the mid-1990's, is the helical or spiral CT. This type of scan owes its name to the helix-like motion of the x-ray tube in relation to the object which is moving through the gantry, while the x-ray tube and detectors rotate continuously. The most advanced version of spiral CT is the multi-slice helical scanner, where four parallel banks of detectors capture multiple slices simultaneously (Goldman, 2007; Michael, 2001). Apart from the medical CT scanning equipment, there is also the industrial one available. The main difference lies in the voltage of the X-rays of the tubes, which is much higher, up to 450 kV for industrial scanning, while for medical CT it is 160Kv (Bonadies,1994).

As demonstrated by the brief historical note on the technological development of CT, the field is experiencing on-going development, given impetus by CT medical imaging capabilities. The CT scanning is a complex process and its successful execution requires a high level of expertise. It involves pre-processing followed by image reconstruction using CT reconstruction algorithms (Azhari, 2010). However, multidisciplinary cooperation and advances in computer science steadily improved the quality and speed of generation of 3D x-ray images, enabling the role of the CT scanner to expand into the field of archaeology, mostly for the study of mummies, but also of other archaeological artefacts such as clay tablets, scrolls, pottery, glass, bronze statues, swords, fossils and paintings (Hughes, 2011).

Morigi (2010) and Casali (2005) presented portable CT scanning systems and applications for large objects, which are of extreme significance for the broader implementation of CT in cultural heritage. Applications on large wooden statues provided information on previous repairs, putties, nails, screws and joining techniques. The conservation state was also reported in detail, including depth of cracks, loss of cohesion or separation between the various parts of the objects assembly, and attack from woodworms in the form of holes in the interior of the wood (Morigi *et al.*, 2010). Another success was the attempt to scan a large globe, of a diameter of about 2.2 m, located at Palazzo Vecchio in Florence. The inner structure of the globe and its iron assembly were visualised, although questions still remain about the presence of another material inside the globe (Casali *et al.*, 2005). This application is important, not only because of the size, shape and historical value of the object, nor due to its specific findings, but because it deals with field of conservation which is not «classical». Globes are artefacts of composite material types, not yet exhaustively examined and documented. As a result conservation operations cannot follow the rules of other artefact types. Also, the demand on XCT samples of tiny details in the microscopic or nanoscopic range is equally important. Micro-tomography uses micro-focus or nanofocus X-ray sources or synchrotron light, and has been applied in a wide range of material types successfully, such as stone, glass, papyrus, wood and bone. X-ray tubes with low focal spots operate at low current and the voltage does not exceed 150 kV (Bradley and Creagh, 2006).

The physical properties of the object under examination, such as density, as well as the required resolution, dictate the choice of instrumentation (Morigi *et al.*, 2010). Hence, medical CT suitable for the human body can be used successfully for cultural heritage applications in artefacts which provide similarities in size, composition and density to the human body. Characteristic examples are mummies and wooden statues. However, metals, such as bronze, cannot be CT scanned with medical equipment, because the necessary voltage for penetration of the X-rays of these tubes is much higher than that of the 160 kV provided by medical CT equipment (Bradley and Creagh, 2006). Several applications proved that this problem can be solved easily by industrial CT, which provides a voltage up to 450 kV. Among them are the XCT of blocks of

soil (Ebinger-Rist *et al.*, 2011) and bronzes (Bonadies, 1994). The most demanding projects and complex materials have used synchrotron light as radiation sources, apart from the micro-and nano-focus and industrial tubes, already mentioned above. Synchrotron sources accelerate electrons inside a ring-shaped device, which emit synchrotron radiation using bending magnets. The energy produced by this continuous radiation is intense, and adequate for high density samples, as well as for faster data acquisition at high spatial resolutions, resulting in high quality results (Bertrand *et al.*, 2012; Zhang *et al.*, 2012). In case of complex, flat, multi-layered objects laminography is the proposed method of CT scanning (Janssens *et al.*, 2010).

3.4.1.2 Applications

3.4.1.2.1 Organics

Since 1977 CT has been largely used in palaeopathological research, the study of ancient mummies (Zweifel *et al.*, 2009). Human and animal remains and fossils were the first objects of cultural heritage and/or archaeological importance to be examined (Conroy and Vannier, 1984). Via CT the fragility of the bones can be documented (Larkin, 2010) and features of extreme importance for mummification, such as the materials and the quality of layers on the skull, can be examined. Also, the use of CT as a valuable tool in dating has been reported (Troalen, 2011). Moreover, CT scanning in case of mummies can provide valuable information about age, sex, stature, diseases and burial practices. Hence, it can offer a broader understanding of ancient civilizations, such as the study of Chachapoyas mummies from Peru (Friedrich *et al.*, 2010). Scientists have detected even prostate cancer in a Ptolemaic Egyptian mummy (Prates *et al.*, 2011).

Organic materials, including wood and canvas paintings, and documentary artefacts, such as papyrus and wooden statues, have been CT scanned as well. Researchers from the University of Bologna in Italy performed CT scanning on two painted wood panels by Gentile da Fabriano. Previous restorations, such as stucco fillings, were documented and the conservation state was recorded. A long transverse crevice and interior holes were detected. In addition, quantitative analyses of damage from microbial infestation were made possible (Morigi *et al.*, 2007) (Figure 87). Another important application of X-ray CT

technology in diagnostic examination is the study of paintings, which present a different geometry and stratigraphy compared to other types of museum objects. Different layers can be examined and hidden details can be documented (Janssens *et al.*, 2010). Moreover, the technique has been applied to ancient and modern bow-stringed instruments for quality analysis and overall characterization (Sodini *et al.*, 2012). Another interesting case study is the application of the technique to waterlogged wooden artefacts, in order to reveal the complex microstructure of the material and the penetration of organic polymers used for conservation operations (Bugani *et al.*, 2009). Micro-CT was also used in order to virtually unroll ancient scrolls and read the hidden text, so as to overcome practical problems of physical manipulation (Baumann *et al.*, 2008; Lin and Seales, 2005). Applications also included reading of sealed clay envelopes with cuneiform writing (Applbaum and Applbaum, 2005).

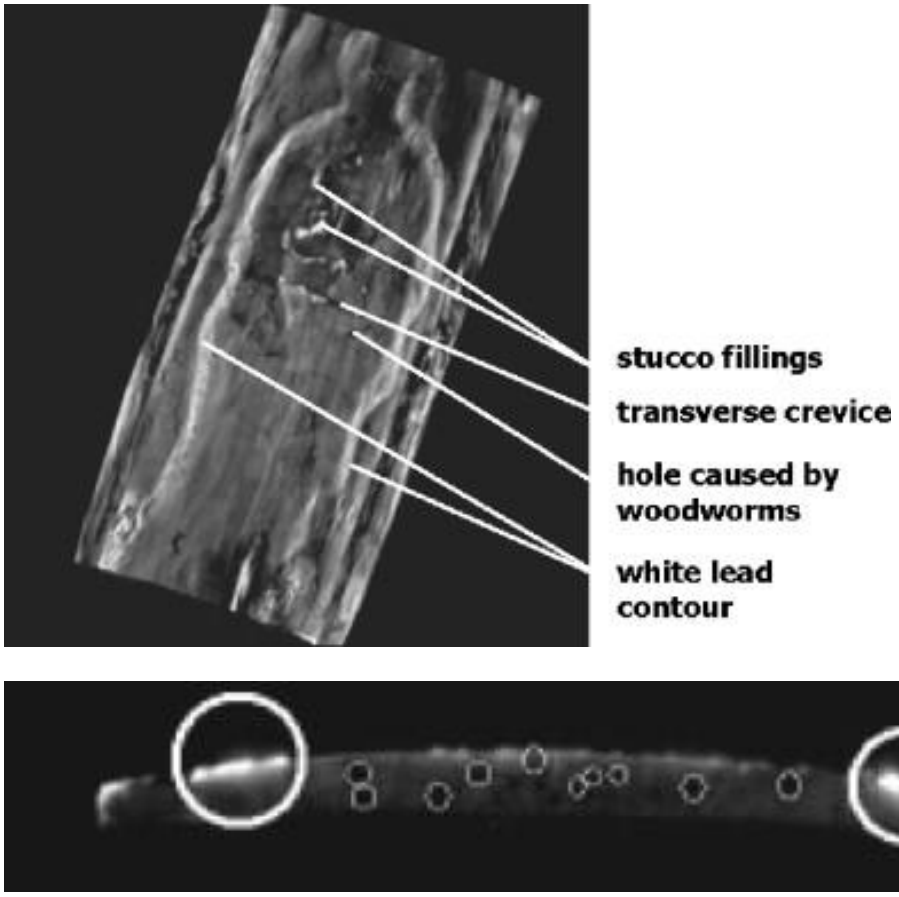


Figure 87: 3D volume reconstruction of a painting on wood attributed to Gentile da Fabriano (1385-1427) (up)Image of a reconstructed slice showing the holes caused by woodworms (below) (Morigi *et al.*, 2007, p.737).

3.4.1.2.2 Ceramics and Glass

In ceramic studies the use of CT is mainly focused on the production of accurate profile drawings for closed shapes and the measurement of capacity. There is no doubt that the development of shapes is a fundamental issue in the study of ancient ceramics. According to previous research, CT offers a much more effective way to perform profile studies, providing not only faster but also more accurate results. Especially in the case of closed-shapes ceramic vessels CT traditional approaches are the most efficient. Also, CT can broaden our knowledge about pottery-making techniques, via the visualization of the inner structure, which reveals techniques and tools used by our ancestors. The quality assessment of the ceramic can be conducted easily, based on observation of homogeneity, air bubbles and cracks. Attachment of parts of the ceramics, foot, neck or handles, as well as restoration operations and presence of other materials can be noted, assisting authentication studies. One of the most significant findings of this research is the determination of the use of ceramics, such as the double- walled jar with an internal system of channels (Jansen *et al*., 2001) (Figure 88).

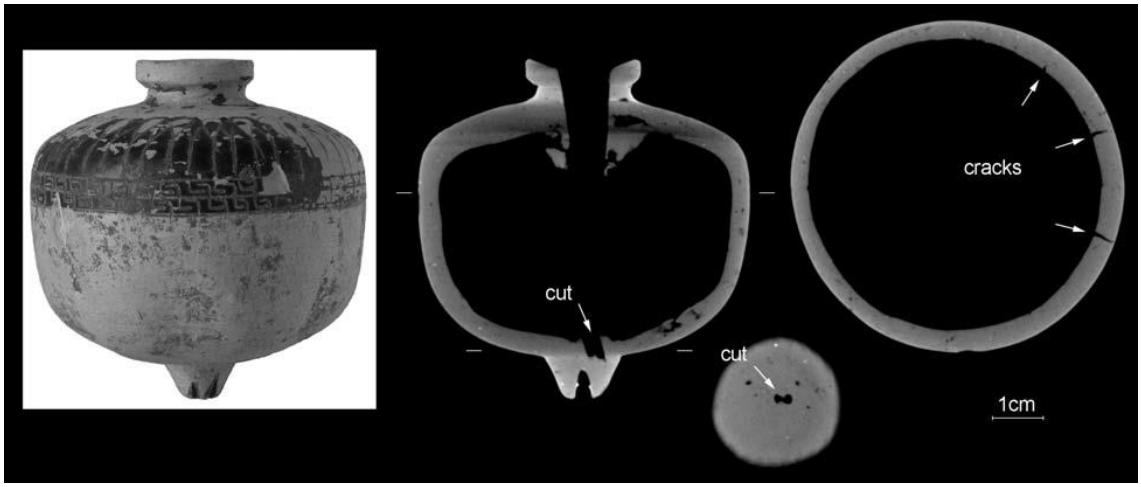


Figure 88: Greek vessel KFUG Dept. Arch. inv. G 56, image and CT cross-sections. The wall thickness varies, three separate sections joined together: the body, the mouth, and the cone end, are visible and cracks in the interior are identified (Karl et al., 2014).

CT has been also applied in the micrometre range with interesting results in glasses and enamels. Its application to enamelled metal artefacts for authentication purposes gave satisfactory results, as enamel composition, structure and metalworking differs between original and non-original parts. Moreover, condition reporting is also crucial in cases of such fragile artefacts as the painted enamel plate. Porosity problems, cracks and cavities, were documented and measured (Linden *et al.*, 2009) (Figure 89). In the case of corroded glass μCT can assist in the determination of the degree of corrosion and in the evaluation of the success of the conservation operations. The corrosion layers can be detected and characterised (Mees *et al.*, 2009). Considering the fragility of archaeological glass, which makes traditional operations not only time consuming but also impossible sometimes, CT is a valuable tool, because it provides data about the location, the quantity, and geometry of glass fragments, assisting their physical recovery. Another advantage of the use of CT is the most accurate reconstruction of the burial with its grave offerings, which enabled advanced documentation and more reliable archaeological conclusions (Jansen *et al.*, 2006). For a ceramics CT scanning case study see section 6.2.4.1.

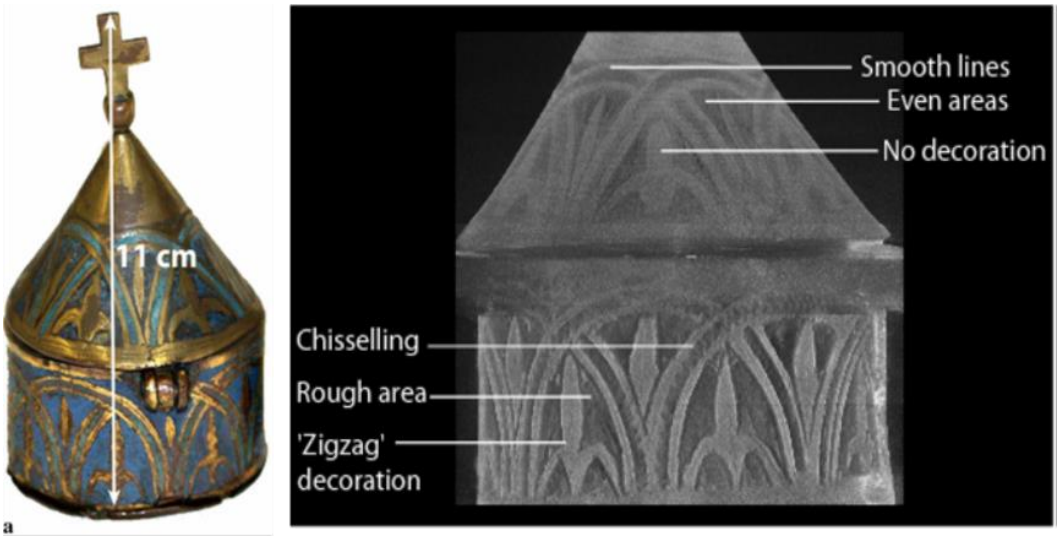


Figure 89: Champlevé enamelled Pyxis, Museum Vleeshuis, Antwerp, Belgium. Digital image and CT scan slice showing the difference in metalworking of the bottom and the lid (Linden *et al.,* 2009).

3.4.1.2.3 Metals

Industrial CT scanning was used for the examination of manufacturing techniques, ancient casting methods, and condition reporting of bronzes (Bonadies, 1994). In this study CT scans reveal and locate variations in the thickness and porosity problems of metal vessels, as well as repairs-restorations, either modern, such as the case of a screw, or ancient ones (Figure 90). The study of interior and exterior structures and stratigraphy, manufacture evidence and material identification was the focus of another study of XCT applied in metal artefacts buried in soil blocks (Ebinger-Rist *et al.*, 2011). From the demonstrated case studies the ability of XCT to offer solutions to conservation problems, providing accurate and fast data without endangering the material integrity of the objects under examination, is stressed. Another useful application of the technique is for fragile composite objects, such as an iron spatha and a sword, including metal and organic components. 3D CT was also applied in Bronze Age weapons, and in particular in a 3000 years old sword with a broken blade, discovered in Austria, in order to detect the cause of the breakage and to study manufacturing techniques (Modlinger, 2011). The inscription on a pocket watch from a shipwreck, which was not recognisable due to corrosion, as well as other mechanical details, were identified using micro-CT (Troalen, 2011). Finally, the study of the Antikythera Mechanism, the ancient Greek astronomic device, included CT scanning of the surviving fragments (Freeth *et al.*, 2006).

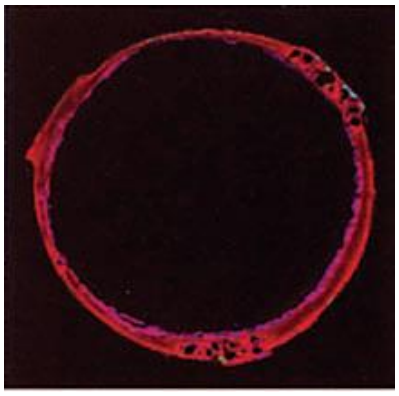


Figure 90: Porosity and variation of wall thickness in a ct slice of a bronze vessel (left) (Bonadies, 1994, p. 79).

X-ray computed tomography is a promising technique in numismatics, assisting identification as well as revealing the dimensions, shape, internal defects and density (Bork, 2011). A comparison between XCT images of corroded coins at Queen's University and traditional cleaning, using mechanical operations, revealed that micro-focus X-ray CT assists identification significantly, and provides better, more detailed images, depending on the metal alloy (Nguyen, 2011; Sullivan, 2011). Moreover, recent research proved that computed tomography can record accurately each individual coin of a hoard, assisting in measurements and providing a secure method for identification (Miles *et al.*, 2012) (Figure 91). For a bronze CT scanning case study see section 6.3.4.1.

Figure 91: CT scan view of a hoard of coins with the exterior pot removed (right) (Miles *et al.*, 2012). Available from: http://acrg.soton.ac.uk/blog/1168/

3.4.1.2.4 Stone

The study of stones and building materials is possible using CT. The internal structure and the overall characterization of stones, such as the network of pores, can be visualised and analysed, both qualitatively and quantitatively (Bugani *et al.*, 2008) (Figure 92). This research highlights the effectiveness of CT in conservation treatments monitoring and conservation materials testing. Limestone and sandstone, which usually suffer from salt weathering, were the subject of another CT study, which aimed to visualize and analyse the distribution of crystals (Witte *et al.*, 2008). The use of micro and/or nano-tomograph is considered important in the case of CT studies of stones, in regard to conservation materials effectiveness and diagnostic examination.

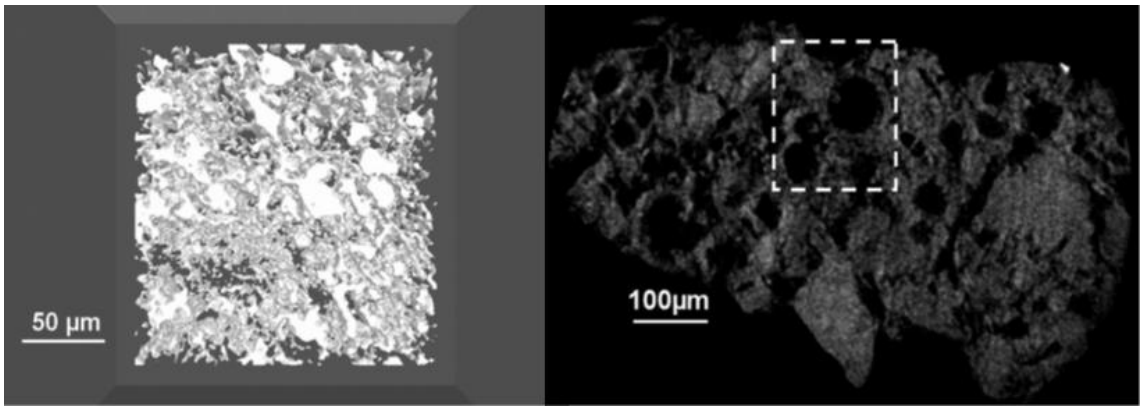


Figure 92: 3D rendering of the pore network of Lecce stone, sample, scanned with micro-CT and reconstructed cross section of an untreated Lecce stone sample, scanned with nano-CT (Bugani *et al.*, 2008).

3.4.1.3 CT and museum strategies

Researchers have adopted contradictory positions regarding museum strategies in the field of CT scanning. Hudges (2011) proposes the acquisition of transportable CT scanning equipment for museums along with high resolution digital imaging, in order to map the photos onto the 3D surface of the artefact generated from the 3D reconstructions. However, the acquisition of such expensive equipment has been considered unnecessary, and instead collaborations with medical centres, hospitals and labs appeared as the most cost effective solution (Applbaum and Applbaum, 2005). Both options have their advantages and disadvantages. The former position's strongest point is the ability of museum professionals to execute limitless scans, an action which promotes research. On the other hand the cost of acquisition, maintenance and employment of specialized professionals is a drawback. The latter option restricts research potential, considering that it is medical scans that are popular all over the world. This type of scanning equipment is appropriate for ceramics, which was the focus of this specific research, but it is not adequate for materials of greater density, such as metals.

The CT scanning results of maiolica ceramics and roman bronzes for the purposes of this study are presented in sections 6.2.4.1 and 6.3.4.1 respectively

CT scanning used to affect the thermo luminescence (TL) signal, but modern equipment reduces the exposure time and uses low energy x-rays, so the impact is believed to be unmeasurable (Ghysels, 2014). In general, there is no relevant research, with convincing evidence regarding the impact of x-rays in the TL signal. In particular, in the case of the ceramics CT scanned for this study, the application of TL was not of interest, considering the safe dating of the jugs based on stylistic analysis and the reference sample of soil from the excavation. Until now the use of TL for dating and authenticity studies (Cosma *et al.*, 2006, Bakraji *et al*, 2013, Bortolot, 1994) is not practiced in great extent.

3.4.2 Magnetic resonance imaging (MRI)

From the above presented literature review one can easily understand the significance of CT scanning in the study of artefacts. Nevertheless other techniques have been developed, such as magnetic resonance imaging (MRI), which uses a radio-frequency waves and a strong magnetic field to visualize structures inside the object under examination, reveal features of equal importance for the study of artefacts. MRI, invented in 1973 and first used during the 1980s, gives different information about structures than cannot be seen with a computed tomography, for example the visualization of hydrogenous materials deep inside thick layers of heavy metals. These visualizations are used so as to define the best treatment, to present inner structures and enhance our understanding about objects (Biro *et al.*, 2011).

3.4.2.1 Instrumentation

In MRI the strong magnetic field is created either temporarily by electric current passed through coiled wires or by permanent magnets. The atomic nuclei are aligned because of the strong magnetic field (resonance). A transmitter/receiver sends and received radio waves. Radio signal disturbs their axis of rotation. Radio waves are generated as the nuclei return to the base line states. After processing of these signals digital images are produced. The most important advancements in MRI technology are the scanning speed, resolution and accuracy as a result of the improved computer 3D algorithms and hardware.

3.4.2.2 Applications

Neutrons can penetrate most of the common metals and detect wood, resin, adhesives, lacquer, and moisture even in low concentrations inside them. Also the homogeneity of the alloy, the casting process and corrosion can be analysed. Characteristic examples are a Roman sword, where according to Lehmann (2006, p.24) '*x-rays reveals the structure of sword and sheath, whereas the neutron image also shows the wooden part of the sheath and the resin used in the restoration*'. Worth mentioning is the value of MRI in case of high lead concentration, where CT scanning is not possible (Lehmann, 2006). An interesting application of the MRI is the differentiation of the exact wax casting technique employed (Van Langh *et al*., 2009) (Figures 93-94).

Figure 93: Hercules Pomarius, digital image and reconstructed neutron scans. (yellow= core material, grey=bronze) (Van Langh *et al*., 2009).

Figure 94: Buddha statue, comparison of digital image, neutron and CT scan (Chankow, 1990, p.95).

After 2000 MRI found application in the study of mummies. The study of hydrated mummies is considered an effective non-invasive diagnostic tool as it produces especially clear images. Characteristic example is the application on a 17th century mummy found in Korea. Overall, the quality of the MR images from the hydrated mummy was superb and the scientific value of MRI in the study of hydrated mummies should not be underestimated (Shin *et al*., 2010). MRI is a very useful tool for assessing the condition of mummies (Gostner *et al*., 2011). It has been applied in an Iron Age body, the Grauballe Man, from Denmark showed a tissue of uniform structure. Low signal areas of a diameter of around 1 mm with individual distances of 3-10 mm were revealed, created by plant roots which penetrated the tissue (Stødkilde-Jørgensen *et al*., 2008). Successful application to dehydrated materials is considered a significant step for the broader application of MRI in archaeology. The earlier examples applied in Egyptian mummies appeared last decade due to the advances of MR scanners. Of great importance is also the development of mobile NMR, which enables in situ data capture. The technique is able to identify tempera and oil medium in paintings assisting authenticity studies (Karlik *et al*., 2007; Ruhli, 2007).

Apart from mummies, another area of research which has been benefited by MRI is the study of stones. MRI made possible to determine porosity, pore-size

distribution, changes of structural porosity, assisting significantly condition monitoring. Also the performance of water-repellent agents in hydrophobic treatment can be evaluated (Borgia *et al*., 2000; Cainaiti *et al*., 2005). The potential of MRI in conservation is not yet examined in depth and future application can significantly enrich our knowledge about artefacts biography as well as materials for conservation and treatments. As far as organic and composite artefacts are concerned MRI can provide data about their internal structure. In the case of inorganic porous materials MRI can evaluate the success of treatment and the performance of materials used.

3.5 Capturing 3d data

The study of cultural heritage objects remains inefficient if their three-dimensionality is not taken under consideration. This is because the most interesting features, in terms of art history, conservation and artefact studies are hidden in a three dimensional coordinate's world, rather than in two dimensions. This is not restricted to complex artefacts. Even objects largely considered as mainly two-dimensional, such as paintings, have very interesting three dimensional features. Brush strokes have a minor, though important, third dimension, which, if examined, can lead to conclusions about painting techniques and materials used in the past. Even the application of the varnish is a record whose documentation is crucial for the overall characterization of a painting. Apart from art historical studies, features which dictate the condition of the painting, as craquelure, cracks and loss of cohesion between the paint layers or the paint and the substrate are observed as slight deformations.

At this point the importance of 3-D recording for documenting, analysing, and safeguarding cultural heritage is well understood, and the huge range of new possibilities is under examination, as demonstrated by the continuous research and development of the field. Three dimensional models are primarily used for documentation, preservation and broadened access, but their contribution is also valuable in research, and for enriching context (Wachowiak and Webb, 2012). Two methodologies for capturing 3d data will be explored, laser scanning and photogrammetry.

3.5.1 Laser scanning

Laser scanning is extensively used for 3D recording in the field of cultural heritage, as it provides the acquisition of 3D data in a relatively short time. Bohler and Marbs define the laser scanner as a device that collects 3D coordinates of any surface automatically and systematically at high rate and in real time (Böhler *et al.*, 2004).

Laser scanners acquire 3D data creating point clouds. These points can reconstruct a triangular mesh, representing the shape of the object or surface, including RGB values for each point. In triangulation systems the laser beam, either a spot or a line, is projected onto the object to be scanned. The object then reflects the beam, which focuses on the lens of a receiving sensor. The sensor is usually a CCD camera. In the terrestrial time of flight or phase-comparison laser scanning systems the laser beam deflected by the rotated mirror reflects into the object surface and returns to the receiving optics. The time of flight system calculates the distance using the time it takes for the beam to return. The phase comparison system measures the difference between the emitted and the received laser pulses, rather than on the time of flight. Furthermore, The Laser Range Scanner records rotation angles around the y- and z-axes, creating quickly a highly-accurate series of sampled points in 3-space.

3.5.1.1 Triangulation scanning systems

For the purposes of the present research triangulation scanning systems are of significance (Figure 95). Other available types, such as time of flight and phase comparison, have found applications in other fields of cultural heritage, especially in architectural and landscape studies, but are not used for portable antiquities. The operating principle of triangulation scanners is 3D recording by triangulating the position of laser light. The set up may employ the position of the artefact on a turntable plate or adjustment of the scanner on a mechanical arm. The overall accuracy of such approaches is around 50 microns. An alternative, less accurate technique employs the use of mirrors/prisms for the automatic measurement of the beam (Barber *et al.*, 2011).

Figure 95: Triangulation laser scanning system (courtesy of Conservation Technologies, National Museums Liverpool) (left) (Barber *et al.*, 2011, p.4).

Accuracy is a basic requirement for the application of 3d graphics in cultural heritage. In artefacts studies, considering the size of the objects and the level of detail required, the high accuracy of the model obtained guarantees its usability. There is published literature on testing of accuracy and quality of different 3D laser scanner systems (Mechelke *et al.*, 2007). The accuracy, along with the resolution, forms the basic characteristics of laser scanners. Each type of laser scanning has its advantages and disadvantages.

A basic limitation of the triangulation scanning system is that a clear view for both the source and sensor is needed, in order to see the surface point currently being scanned. Also, surface reflectance properties affect the quality of data that can be obtained. Simple laser scanners offer poor results when the object under examination has unreflective surfaces, as no range value can be computed. When the object surface is highly reflective, surfaces or dust particles interfere, so that the range values turn to be skewed. Also, for materials with characteristic subsurface scattering, it proved to be ineffective. Another limitation is the fact that triangulation scanning systems generate extremely large datasets. The presence of bright sunlight can affect the data acquisition process; as a result it is more appropriate for interior scanning.

Computer software is necessary in the operation, processing, visualization and utilization of the laser scanning data. This software is usually designed in order to be compatible with large volumes of 3D measurements. The laser scanner software combines the sensor- signal with the known separation between it and the mirror, computing an array of depth values. The created point cloud turned into useful 3D data, a 3D model, through the registration process. All the individual range images were registered or aligned in a single coordinate system. The three dimensional viewer offers the ability of performing simple transformations. A simple desktop PC may be inappropriate for the manipulation of the laser scanning output, because it acquires high computing power. Other computer requirements are a 3D graphics accelerator, a RAM memory, a hard disk, a good quality monitor and a processor.

3.5.1.2 Applications

Baribeau (1995) emphasised the usefulness of laser scanning in providing access to collections and enhancing measurement, comparison and study of artefacts. Nowadays, there is a long list of research projects that used laser scanning as a digital capture recording technique. The most renowned example is the application of laser scanning in Michelangelo's statues (Levoy *et al*., 2000) and cuneiform tablets (Anderson and Levoy, 2002; Kumar *et al*., 2003). Laser scanning has been used for a large variety of artefacts types, such as skeletal material (Kuzminsky and Gardiner, 2012).

Among the most interesting applications of laser scanning in artefacts studies was the case of a gilded bronze Anglo-Saxon brooch (Figure 96). It was scanned using arm-mounted triangulation-based laser scanning. The scanning equipment had a 70mm stripe width with an accuracy of +/-0.1mm at a working distance of 50mm. Because of the fine detail and the reflectance properties of the material further processing was necessary. The laser power during scanning was not stable enough to capture complete data light and dark areas (Barber *et al*., 2011). The laser scanning of the Ferryland cross is also worth mentioning (Logan *et al*., 2010) (Figure 97). Of great interest for conservation is Kottke's research, which underlines the practical, hardware and scanning limitations in stone degradation monitoring at the micro-scale. Furthermore, she proposes cloud-to-cloud surface, profile or section

comparisons and the use of the point cloud as a referencing model in a database for dissemination, communication and documentation of large scale projects (Kottke and Hinchman, 2009).

Figure 96: The Ferryland Cross (left), the digitally reconstructed image (Logan *et al.*, 2010, p.128-131).

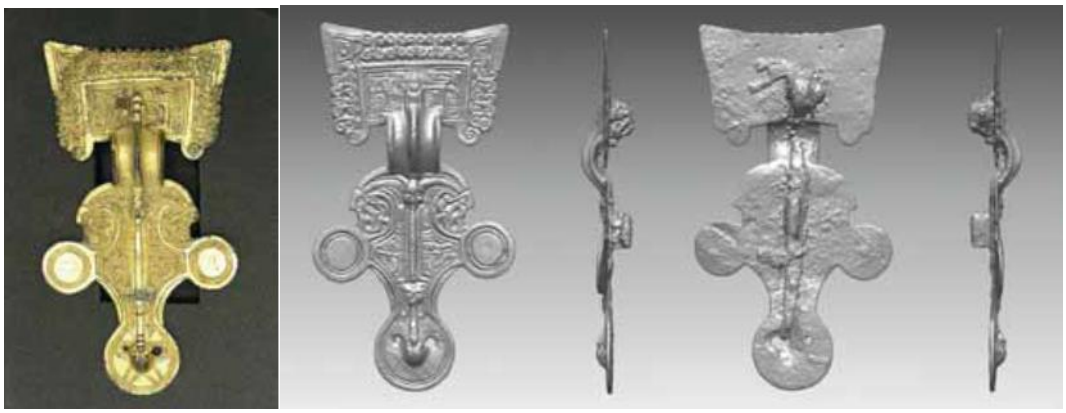


Figure 97: Saxon great square-headed brooch image and screenshot of the 3d model (Barber *et al.*, 2011, p.27).

The translucency of surfaces poses problems for the laser scanning application, because of light scattering. Similarly reflectivity, which leads to specular light reflection, may result in problematic data capture. The scanning equipment has been developed and successful applications on shiny or translucent objects have been presented (Rodrigues and Kormann, 2012), but these materials are still considered as the most difficult to capture. The use of sprays or powder is not acceptable for cultural heritage artefacts, because of the contamination of the original material and the need to apply soap for their

removal. The Scanning from Heating (SFH) method proposed for transparent materials, such as glass (Eren, 2010), requires heating of the object and as a result may introduce unwanted alterations or even damage to the artefacts, therefore its application in cultural heritage is limited.

3.5.2 Photogrammetry

The term photogrammetry appears in the literature in 1867, while the first International Society for Photogrammetry (ISP) was founded in 1910 and renamed in the 1980s as the International Society for Photogrammetry and Remote Sensing (ISPRS) (Kucukkaya, 2004). The ISPRS cooperates with the International Scientific Committee for Documentation of Cultural Heritage (CIPA), one of the international committees of ICOMOS (International Council on Monuments and Sites), having as a goal the enhancement of surveying methodologies, and in particular the advanced recording, monitoring, preservation and restoration of architectural monuments, objects or sites. This signals the recognition of the contribution of photogrammetry and remote sensing in archaeological research.

Although photogrammetry can be applied at a very wide range of scales, a widely known categorisation is Aerial and Close-range Photogrammetry (CRP), according to the location of the camera in relation to the imaged object. Although the former found many applications in cultural heritage, it goes beyond the scope of the present study, as it is strongly connected to topographic photogrammetry, terrain, excavation models, buildings and large architectural structures, far away from portable antiquities and museum conservation practices.

On the contrary, CRP, or Image Based Modelling (IBM), used to describe the construction of a three dimensional model of an object from two dimensional images, where the camera is mound on a tripod or it is hand held, has been applied for digital capture of archaeological artefacts and works of art. The difference in 3D digitization of cultural heritage between objects and monuments has been discussed (Pavlidis *et al*., 2007). However, the most widespread use has been for monuments, historic buildings and facades rather than portable antiquities. It has been used for documentation, monitoring of

structural problems and authentication studies, as it provides advanced volumetric perception and enhanced material description (Yilmaz *et al.*, 2007).

IBM is the most complete, economical, portable, and flexible, as well as widely used technique for 3D modelling. But of course there are problematic aspects. Fully automated procedures are criticized as useful for visualizations but inappropriate for documentation, because they lack accuracy. Other options to be considered are the semi-automated, where human intervention is necessary for processing. Their great advantage is their ability to deal with complex geometry, while the necessary level of human interaction can be considered as a drawback (Remondino and El-Hakim, 2006). Hence, the conclusion can be drawn that fully automated application cannot meet conservation needs, where the accuracy and complexity of artefacts reaches higher levels than ordinary cultural heritage recording and documentation needs. On the other hand the presence of a long list of software for photogrammetry and image based modelling is promising.

3.5.2.1 Software packages and applications

Low cost commercial or even free software with affordable equipment succeeds in 3D modelling of archaeological structures, such as the case of the temple G1 of the archaeological area of MySon in Vietnam, providing valuable results for restoration design (Barazzetti *et al.*, 2011). Within conservation, photogrammetry can play a significant role, basically because of its flexibility. The photogrammetric dataset can be reprocessed and reused, in order to create a variety of representation for different purposes (Lagerqvist, 1999). There are several photogrammetric software packages available either at low cost or for free:

- Photo Modeler Scanner, distributed by Eos Systems, (Eos Systems, 2014)
- Agisoft Photoscan is capable for textured 3D model extraction (Agisoft, 2014)
- Microsoft Photosynth (Microsoft, 2014)
- The Evo suite, the ZScan instrumental survey system and the stereo-photogrammetric System, Cyclop II, by Menci Software (Menci Software, 2013)

- the ARC 3D web service developed by the VISICS research group of the K.U.Leuven in Belgium (VISICS K.U.Leuven, 2014)
- the ORPHEUS/ORIENT, of the Vienna University of Technology (Vienna University of Technology, 2014)
- Autodesk 123D Catch (Autodesk, 2014)
- Smart3DCapture Scanner, designed by ACUTE 3D (Acute 3d, 2013)

3.5.2.2 Turn table approaches

For complex objects the creation of 3D model from 2D imaging is problematic, and there is a need for careful design of the imaging environment, including the geometry, lighting, and background in relation to surface properties. An image acquisition system, adequate for small artefacts, is proposed, consisting of a turn table, a digital camera and a computer. By rotating the turn table, where the object is located, images are taken, which finally are used in order to create the shape as a triangular mesh and the appearance as a texture map (Yılmaz *et al.*, 2003) (Figure 98). Similarly, the position of the object on a turn table, and the successive capturing of images with a stable camera, has been proposed for the creation of three-dimensional models of objects. In that way the camera's location can be accurately calculated. One image was captured on every 10°, resulting in 36 images. After simple processing and rather limited human interaction, the 3D object is created with Surfer 6.01. CAD programmes can be employed for further editing of the model (Jacobs and Tsioukas, 2004).

The two strategies presented above use a similar image capture approach, while the algorithms employed for 3D model generation differ. Both have been proposed for small artefacts. The common feature is the rotation of artefacts. However, questions arise about the risks of such capturing methodology and the safety of artefacts during rotation. Contemporary museum standards may not allow the endangering of objects integrity, and consequently this data acquisition approaches should be approached cautiously for the safeguarding of cultural heritage. Hence, the use of turn tables is not recommended. Instead, data capture with static objects and moving cameras is the most appropriate methodology.

Figure 98: 3d model acquisition system for three-dimensional modelling of small artefacts, consisting of a turn table, a camera and a computer (Yılmaz *et al.*, 2003).

3.5.2.3 Applications

The digitising project of the wooden statue of Maddalena by Donatello, which survived the flood of 1966, is an interesting case study because of its size, around 1.80 meters, as well as its complex three-dimensionality. These features, in addition to the high need for accuracy, lead to various problems during the acquisition procedure, which employed a close-range digital photogrammetry software (ShapeCapture). Moreover, photogrammetry enabled the dimensional verification on the 3-D model, improving the alignment procedure (Guidi *et al.*, 2004).

An application of a photogrammetric-computer vision methodology for 3D documentation of excavated archaeological features, including skeletal remains, gave accurate results without the drawback of necessary human intervention. A set of digital images with sufficient overlap was captured, and the rest of the process was performed automatically in order to align the images, calculate a point cloud and texture map the model. It was characterised as a cost-effective, scientifically reliable approach, which is an improvement compared to traditional techniques (De Reu *et al.*, 2012).

For Microsoft Photosynth, an image browser for 3D photo models, a set of images from 20 to 300, or sometimes more, needs to be uploaded in order for the software to analyse them and reconstruct a 3D point cloud. The process of downloading a point cloud and further processing to a 3D object reconstruction is described by Pomaska, using Wireshark, a network protocol analyzer, and a Python script, to convert the binary files into text files, mesh lab and blender software (Pomaska, 2009). Digital photogrammetry with the ZScan enables quick and high quality data capture, even at the millimetre range, and proved to be useful for archaeological, architectural and historic-artistic artefacts (Salonia *et al.*, 2009) (Figure 99).

Figure 99: The roman Balteus and detail of 3d model obtainable through the use of ZScan system (Salonia *et al.*, 2009, p.60-61).

Proposals for further development of photogrammetry can be found in section 4.3.2.2. The proposed visualization methodologies are trialed in section 05.4, and evaluated in section 5.5, leading to conclusions regarding the contribution of PG in conservation in section 5.6.

3.6 Synergistic approaches to digital capture

There is an obvious trend in research directed towards synergistic approaches to digital capture. The combinations of technologies lead to more efficient digital capture and presents new possibilities for research. Examples of combined methodologies have been proposed for already known techniques, such as photogrammetry, laser scanning, RTI and multispectral imaging. Interestingly enough, synergistic approaches are evident also in new

techniques under development, such as the AR technique (for a discussion about AR see section 2.3.3.1.1), which acts complementary to RTI, sharing the same datasets. So, the idea of combined use of technology to gain maximum information has found a place, not only in separate applications and case studies, but also in the development of new techniques.

RTI can be used as an explicit example for an analysis of synergistic approaches, because it is flexible enough to implement different photographic set-ups, according to the needs of the photographed object.

> '*While RTI is effective for surfaces where texture (carving or engraving) is the primary means of data storage, other methods have to be found for situations where colour contrast is key, as with ink on parchment or papyrus*' (Lexoux, 2013, p.114).

Multispectral RTI provides a practical solution for this problem. It is complementary to normal RTI technique, with significant potential for a broad area of materials and artefacts types, including painted surfaces, canvas, documentary artefacts, engraved stones in poor conservation condition, restored glass artefacts, painted or engraved ceramics with encrustations, mortars, paper and archival material. The experimentation for the simultaneous capture of both spectral and textural data by Hewlett-Packard and Cultural Heritage Imaging (CHI) researchers reached the conclusion that the technique is feasible (Redman and Mudge, 2007). CHI has been experimenting with multispectral RTI and conservators emphasised its research potential (Castriota and Serotta, 2011). IR and UV RTI have been applied to an oil painting, as appears in the RTIiCAN blog, with the Osiris IRR camera/scanner (Gabov, 2010). A combined RTI and infrared methodology was used for the study of ancient Dead Sea scrolls, in order to reveal the text and examine the condition of the parchment. This successful project demonstrated a promising methodological approach for the study of documentary artefacts, but also the necessity for further experimentation (Caine and Magen, 2011). An interesting approach combining IR imaging, RTI and dense-range photogrammetry in a mosaic pattern has been proposed for a 19th century British painting of large dimensions (Bennet, 2013).

The datasets from RTI do not necessarily originate from a dslr camera. The virtual RTI method is an alternative to normal RTI which provides the opportunity to the viewer to interact with 3d data using the RTI methodology. The virtual RTI is a combination of Polynomial Texture Mapping and other reflectance transformation techniques with photogrammetry and non-contact digitising. Instead of physical domes or rotation arms, the virtual RTI uses animated virtual domes, which leads to a sequence of rendering of the 3d model, processed using the same methods as normal RTIs (Earl *et al*., 2010) (Figure 100). One of the most exciting recent developments in data capture is the Underwater RTI. David Selmo, from the Centre for Maritime Archaeology, University of Southampton, completed data capture in a pool (Selmo, 2013). This successful application has great potential for the broader appreciation of RTI as a diagnostic and recording tool in underwater environments (Figure 101).

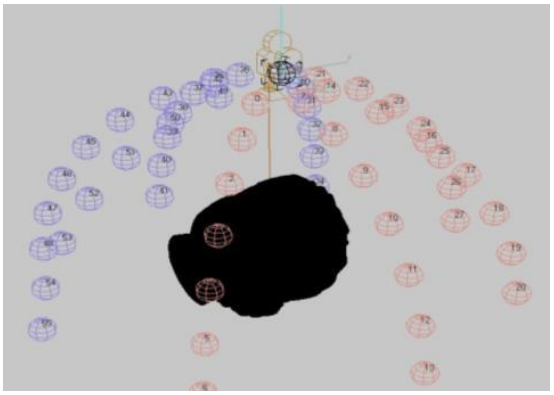


Figure 100: One of the virtual PTM domes set up over the scanned Amazon in 3ds Max 2010 (Earl *et al*., 2010).

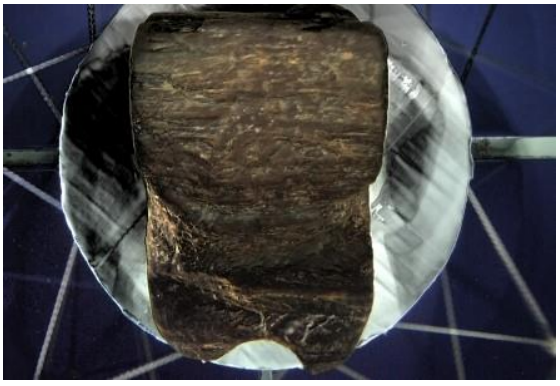


Figure 101: Underwater RTI visualization (Selmo, 2013).

It is also worth mentioning the large number of research articles about combinations and comparisons of laser scanning and photogrammetric approaches for cultural heritage documentation (Boehler and Marbs, 2004; Grussenmeyer *et al*., 2008; Ioannidis and Tsakiri, 2003; Lambers *et al*., 2007; Kadobayashi *et al*., 2004). For buildings and sites, laser scanning and/or photogrammetric techniques can lead to similar results for flat and regular shaped objects (Grussenmeyer *et al*., 2008) or complex geometry and irregular shape building components (Yastikli, 2007).

Kadobayashi et al, after comparison and experimentation on the combined use of laser scanning and photogrammetry on Byzantine ruins, proposed combined approaches based on practical experience, accumulated know-how and the requirements of each project (Kadobayashi *et al*., 2004). Similarly, a combination of scanning and photogrammetric techniques is recommended when line- and surface-based structures have to be captured (Boehler and Marbs, 2004). The combination of different techniques can lead to successful results in the case of complex structures. Cracks and degradation phenomena on materials can be captured and distinguished in the final visualisation (Núñez Andrés *et al*., 2012). Lambers (2007) reports successful results from the combination of photogrammetry and laser scanning, underlining the efficiency and the flexibility of such approaches, as well as the opportunity to examine different levels of resolution and different viewing angles, leading to an enhanced multi-level architectural, structural, and functional study of archaeological sites. In the case of a marble statue, comparisons of laser scanning and photogrammetric techniques conclude that the former is faster and fully automated (Ioannidis and Tsakiri, 2003). A combination of photogrammetry and laser scanning enabled the successful three dimensional recording of a demanding type of artefact made of transparent plastic, at a millimetre level of accuracy. The improved documentation of two sculptures, recorded following this combination technique, was greatly appreciated by conservators (Robson *et al*., 2008).

Among the proposed combinations of approaches are photogrammetric techniques for object shape and texture and laser scanning of the object's surface (Radosevic, 2010). In an architectural survey, the main structure was captured by photogrammetry, while for the final details laser scanning was

used. However, there are other methods of integration of the two techniques still to be exploited (Guarnieri *et al*., 2005). For example, in the statue of Pepi, researchers document the seams and rivets with photogrammetry, and continue with measurements based on laser scanned data. This combination provided enhanced information for the artefact, useful for its restoration, conservation, technological investigation and documentation (Heinz, 2002).

There is a growing interest for the recording of 3d data with multispectral texture, as it is believed that these augmented models can enhance the analysis and study of artefacts, in particular for conservation purposes (Simon *et al*., 2013). The first multispectral laser scanner prototype has been used for the non-destructive diagnostic examination of damages on building surfaces (Hemmleb *et al*., 2006). The ICCOM-CNR has applied the multispectral 3d technique to wall paintings from the tomb of Scimmia (Palleschi, 2013). During the SUMUS (System for 3d Multispectral Imaging) project the multispectral 3d methodologies has been applied for the restoration of the Annunciation of Benozzo Gozzoli. Although multispectral 3d capture is feasible and can provide useful data, it has found limited applications, mainly due to the problems in capturing and processing of the multispectral 3d data (Figure 102).

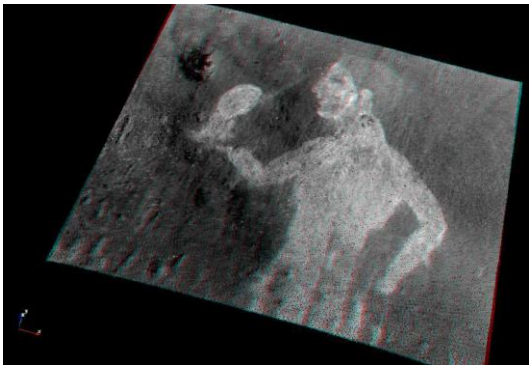


Figure 102: Chiusi, tomb of Scimmia, multispectral 3D (Palleschi, 2013).

3.7 Summary

Contemporary practice has shown that the recording and examination of objects of art and antiquity can be performed using a variety of modern technologies. This chapter presented an overview of artefacts digital capture techniques for capturing texture and colour, data beyond the visible, 3d data

and volume. Although many new scientific techniques and technology were introduced in the second half of the twentieth century, conservation was slow to adopt them, but eventually did so in order to reduce speculation and deduction (Fotakis *et al*. 2007). This trend applies to the application of digital techniques too. Although research has been directed towards the application and further development of these techniques, a comparative analysis based on their capabilities and limitations from a conservator's perspective is missing, and there is a large area for improvement in the field of digital capture of artefacts so as to meet conservation objectives. The critical evaluation of these methodologies, based on their contribution to conservation objectives and actions, as well as proposals for further development, are discussed at a theoretical level in the following chapter.

Part 2: Evaluating and enhancing digital conservation

Chapter 4: Proposals for enhancing digital conservation

4.1 Introduction

In part one the digital technologies used in current digitization and imaging practices were presented and their potential discussed via a list of digital solutions to common conservation and restoration problems. Artefacts' digitization (Chapter 3) and the application of digital techniques in conservation practice (Chapter 2) are crucial for the broader application of digital technology by the cultural heritage sector in general, and by the conservation community in particular. The focus of this chapter is to introduce the proposed developments of digital applications in conservation at a theoretical level.

Following the literature review on digital capture techniques in Chapter 3, a comparative analysis of digital capture techniques, and proposals for the developments of digital capture, based on conservation needs, are presented in section 4.3, in an attempt to facilitate visual analysis. The virtualization of visual analysis can potentially enhance current practices of human-object interaction, for both museum professionals and the public, and is considered to be a prerequisite for the novel methodologies to be incorporated more effectively in conservation practice. Following the discussion on conservation documentation problems and digital solutions in Chapter 2 (sections 2.2.3 and 2.3.4), the role of 3d documentation in conservation is defined and novel systematic documentation approaches are proposed in section 4.4. Then, the way these ideas are reflected on conservation theory is presented via new mapping on RIP schemas in section 4.5.

Apart from methodological issues, the interrelationship between physical and virtual artefacts needs to be examined in order to determine the role of

virtualization in conservation. In order to achieve this goal it is necessary to draw a distinct line between the virtual reality and the physical world. In that sense a critique about the physical and the virtual artefacts (section 4.2.1) from the conservation perspective is the initial point for a discussion about the changes introduced via the virtualization, which influences the museum sector as a whole. In an attempt to bridge the gap between the physical and the virtual artefact the implementation of mixed reality approaches is proposed. The opportunities offered by mixed reality approaches are also presented (section 4.2.2).

4.2 Interrelationships between physical and virtual artefacts

The way conservation participates in the construction of knowledge based on ethics and a rationalistic scientific approach, as well as the inter-relationship between conservator and objects, has been discussed in the conservation literature.

> 'Conservation *focuses on the preservation of cultural knowledge in objects, the authentication of which creates an inseparable bond between the conservator and the conserved object*' (Malkogeorgou, 2011, p.443).

Do virtual objects represent another level of the bond between objects and conservators, or is their role solely the vehicle or the medium for the successful execution of a conservator's project? This still remains a question to be answered. Nevertheless, the analysis of interrelationships between virtual and physical artefacts, in the following section, will highlight the potential for an enhanced conservation museum strategy towards preservation and restoration of artefacts. This enhanced relationship can potentially improve the museum's effectiveness, and also support its social responsibilities for public access without sacrificing the safety of artefacts.

4.2.1 Physical and virtual artefacts: a critical approach

The contemporary ideas of minimal loss of potential meanings (Munoz-Vinas, 2005) or post- minimal intervention (Villers, 2004), which express the development of minimal intervention, are embodied in the digital approaches

towards conservation. As discussed in Chapter 2 (for conventional conservation methodology problems and digital solutions see section 2.2 and 2.3), via virtual artefacts the material integrity is protected and the interaction of the conservator with the original physical artefact is limited, reducing risks and potential damage from reconstruction failure, mishandling and display. Virtual models of artefacts enable better preservation and substantially improve the re-treatability of original artefacts. The interventive operations on the authentic materials are limited, as revelation activities are mainly executed virtually. The value of the object, its intellectual meaning, is better protected and has a higher chance of correct interpretation, because the examination of the physical signs is enhanced, thanks to advances in digital tools. The original material is preserved in the most objective way, without being affected by subjective judgement.

Nevertheless, there are aspects of the real object that 3d modelling cannot capture. In terms of authenticity there is an obvious difference between the replica and the original, but a values analysis[19] manifests the huge gap between replicas and real artefacts. Although the aesthetic and educational value of real and virtual objects is the same, the artistic, historical, research and scientific, age, sentimental, monetary, and rarity values are differentiated. The virtual model fails to preserve the physical evidence of past civilizations (Caple, 2009). The process of digitization and modelling is not synonymous with material preservation, and as a strategy does not provide an ultimate solution to the preservation problem, although it contributes to present and future re-investigation indirectly, by providing a secure environment for the original artefact, neither contaminated by chemicals nor further deteriorated.

In that way, the original is transferred in an advanced re-examinable state for future scientists. The potential benefit for material culture specialists when they study the virtual model is the opportunity for improved research, both qualitatively and quantitatively. But the actual remains of ancient civilizations, the physical evidence, should be preserved, using experience and knowledge

[19] Values analysis is a method proposed by Appelbaum (2007) and has never been applied in order to gain a better understanding of virtual artefacts before.

from preventive restoration and conservation treatment, in addition to virtual reconstruction.

It has been argued that informational preservation[20] does not create an improved state of conservation for the original object, which becomes more readily dispensable for some people (Munoz-Vinas, 2005). This sceptical approach towards computer applications in conservation uses the basic argument that the digital object and its possible replication can lead to the artefact being treated with ignorance. This opinion is based on the fact that the virtual reconstruction does not ensure the physical preservation of the original artefact, though it does not necessarily follow that the original will end up in a less favourable state. Just as virtual museums cannot replace physical ones, but are considered to be reflections and extension of the latter (Sylaiou *et al*., 2009), the virtual object is an extension of the physical one. Furthermore, the virtual and the original object are created to fulfil different goals in different historical times and under different circumstances, so they should not be seen as antagonists, but as complementary approaches (Newell, 2012).

A virtual reconstruction of an artefact cannot diminish the overall value of the original. This approach can be considered as a general critique to conservation, and not solely against digital applications. Questions arise whether or not each interpretation is based on accurate scientific data. Considering that these actions are executed by professionals, the respect for cultural heritage in general, and for archaeological evidence in particular, should be taken for granted. If this is not the case, the fear of misleading interpretations may apply not only to virtual restoration and physical reconstruction, but also to remedial conservation treatments, the latter being more dangerous because they may cause irreversible alterations to the artefact's material integrity. However, despite these dubious views about virtual reconstruction and conservation practice, the profession is now mature enough to realise the advantages of digital recording techniques, and the integration of digital techniques in conservation is welcomed. Furthermore, the acceptance of this critique against digital restoration means that the scientific community will deny all the other

[20] Informational preservation is defined as the conservation related record producing activity which enables the virtual representation of an artefact (Munoz-Vinas, 2005).

basic objectives of conservation, by underestimating material integrity and durability issues. At the same time this will signal disapproval of the foundations of the profession.

Moreover, ideas against virtual reconstruction contradict the multidimensional contemporary approaches to conservation, which are reflected in professional guidelines. There is no doubt that material preservation is the cornerstone of conservation as well as interpretation, considering that every action taken is a result of a particular interpretation. The success of conservation operations depends on the conservators' ability to understand the interaction between material and non-material information. Denying other methods of interpretation outside the object is a lost opportunity to understand the object better, to distinguish the '*ideal state*' and proceed to better treatment (Appelbaum, 2007). In addition to the virtual artefact the implementation of mixed reality approaches provides an advanced level of communication between the conservator and the original artefact. These techniques were introduced in section 2.3.4 and will be critically approached from a conservation perspective in the following section.

4.2.2 Implementing mixed reality approaches

Barker and Smithen (2008) demonstrated the challenges for balanced preservation and use in order to facilitate the complete museum experience. They refer to the future of museum practice providing different scenarios, by assuming the exaggerated or limited valorisation of authenticity and material integrity. Nevertheless, they predict that the most likely scenario stands in the middle stating that

> '*the conservator will likely remain guardian of the "ideal" state of an object, and indeed will continue to add his or her voice to the debate on what this "ideal" state is; in practice, though, she or he will be prepared to accommodate less than ideal conditions so that the work completes its function by being seen and experienced*' (Barker and Smithen, 2008, p.102).

The use of technologies, which made possible the closer alignment of the physical and the virtual words, such as tagging, haptic, projections and 3d

reproductions, are issues of great importance, in the explorations of this '*ideal*' state and their application can significantly assist in solving conservation dilemmas.

> '(*Biology*) *moves from a discipline primarily devoted to observation and experimentation to one reliant for new advances on the manipulation and analysis of digital data and models*' (Frischer, 2011, p.27).

However, the example of biology, can hardly find total appreciation in conservation because, as Brandi (1963) noted, conservation needs to be loyal to the material form of artefacts. Mixed-reality approaches bridge the gap between the physical and the virtual world. As discussed in section 2.3.4.1.1 haptics provide an innovative form of communication between humans and digital artefacts, providing the opportunity to experience the virtual world via touching. Tagging (2.3.4.1.2) enables the easy and fast data collection and sharing and 3d projections (2.3.4.1.3) can create illusions to the viewer, blending the physical object with virtual reality scenes. The conservation potential of these technologies has not been evaluated yet and will be discussed in the following sections.

4.2.2.1 Haptics

Zimmer and Jefferies' (2007, p.1189) prediction that haptic technology '*will change the notion of space and of Interaction'* is fully justifiable. This technology can potentially change the notion of interaction with the object in conservation and restoration activities. The work already published on the application of haptic virtual reality environments in conservation is limited and focuses on conservation training rather than practice. Geary proposes a haptic virtual reality environment for simulating conservation operations so as to provide an enhanced training tool for paper conservation, including visual, aural and touch stimuli (Geary and Sandy, 2004).

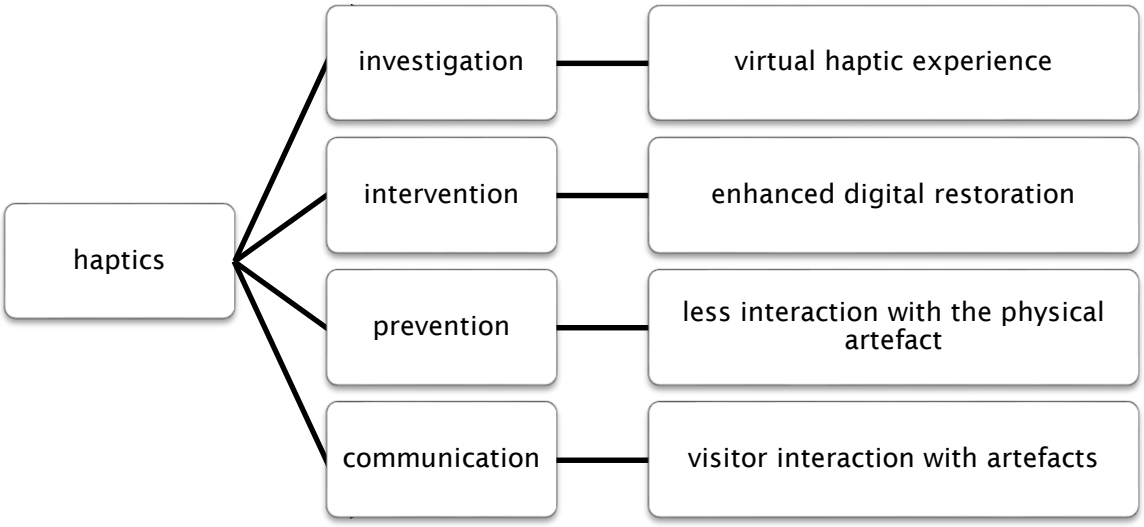
But haptics can potentially be a valuable tool for conservation purposes other than training. The option to do and undo virtually an operation is a more efficient and safer reconstruction methodology in comparison to the contemporary common practice of physical joining and separation of pieces. In the case of fragile material types, such as glass with thin layers, this is

undoubtedly of utmost importance, considering the practical problems of physical restoration. In addition, virtual execution of operations enables conservators to store information about previous stages of the artefact, during a virtual exploration, leading to better documented operations. At the same time improved categorization, stylistic analysis and dating is possible, especially for the reconstruction of fragmented artefacts, where decision making should be justified by evidence, as well as by archaeological materials found intact.

Although this can be done in front of a computer screen, the ability to feel such actions is considered advantageous, because it makes use of the valuable conservator experience of handling real objects and instinctual choices employed. Hence, the use of haptic technology offers the possibility to significantly improve the process of virtual reconstruction / digital restoration of artefacts. Nevertheless, the main drawback of this methodology is the high cost and technological needs.

According to Hespanha (2000) the haptic application in many cases demands that users interact with each other as well as with other objects during explorations in a virtual environment. In this virtual haptic world diverse kinds of devices can be used, making possible the simultaneous collection and broadcasting of information to multiple users in a network (Hespanha *et al.*, 2000). This virtual haptic collaboration can potentially revolutionise the way specialists study objects and communicate their ideas with their colleagues. For conservation such interaction between professionals and the objects is synonymous to a unique experience, meaning that in practice it is not possible for two conservators to examine the physical artefact at the same time. Virtual haptic collaboration introduces new ideas, which may transform contemporary approaches and well accepted methodologies, apart from geographical limits, preventive conservation issues and time constraints, which would not be considered a drawback. Moreover, this virtual collaborative haptic environment encourages a more active collaboration and broadens the appreciation of artefacts.

From the above, it becomes apparent that conservation virtualization, which is the focus of this research, can be benefited by the use of haptics technology, particularly the field of examination, preventive conservation and virtual reconstruction (Graph 10). Similarly, RFID/NFC and QR codes offer opportunities primarily for enhanced documentation by combining effectively the physical object with relevant visual and textual data.



Graph 10: The potential of haptics in conservation practice (Graph author's own).

4.2.2.2 RFID/NFC and QR codes

The previous implementation of RFID/NFC and QR codes in museums are focused on museum guides (section 2.3.4.1.2). The potential of these technologies in conservation has not been explored yet, although conservation can equally benefit from such applications. In particular RFID/NFC and QR codes can be used for labelling, conservation reporting-condition and environmental monitoring, as well as during interventive conservation.

Tags can be used instead of traditional labels on objects (alphanumeric codes written or attached to the objects, which specify provenance information) or boxes. In that way collection storage and management can significantly improve. The tags can be linked to the collection database where object related information can be retrieved and analysed by the user. Time consuming actions, such as searching in storerooms among thousands of artefacts can be

accelerated. In large conservation projects, for example when hundreds of fragments need to be identified, each one is being labelled. The information written on the label is crucial for the archaeological interpretation, for the determination of the causes of damage and the reconstruction of the history of the monument. The use of tags as labels enables the easier management of such a large scale project and may lead to safer conclusions.

Considering that RFID systems cannot only identify objects, but can also retrieve information about their location and status (Tan, 2010), their application is important for condition reporting. During collection condition surveys the conservator can easily access data from previous surveys and compare them to the present state of the artefacts via object hyperlinking between the object and its conservation records. In that sense the conservator reports not only become more accessible but also become more usable. These technologies can assist environmental monitoring. Via AIDC techniques the physical object can be linked to a globally accessible virtual object that contains both current and historical information on that object's physical properties and sensory context (Welbourne *et al*., 2009). The tags can be linked to the environmental conditions, retrieving data about the environmental parameters of storerooms or displays, so as to achieve effective and easy environmental monitoring of the areas of interest and condition reporting of the artefacts.

The link between the conservation biography of objects and conservation operations to the object themselves can be generated in a way similar to the ideas of Tales of Things and Internet of Things. The latter can be defined as:

> '*Things have identities and virtual personalities operating in smart spaces using intelligent interfaces to connect and communicate within social, environment, and user contexts*' or as '*Interconnected objects having an active role in what might be called Future Internet*' (EPPoSS, 2008, p.4).

In the Internet of Things era the interaction between human and things, and between things themselves will be possible (Tan, 2010). The Conservation Tales of things and/or the Tales of conservation processes can be produced as well. The main contribution, apart from the connection between physical objects and digital data, will be the development of a huge amount of

information related to conservation operations and conservation related information about each object. This data can be used by contemporary conservators as well as future generations as a basis for the evaluation of success of specific conservation treatment methodologies.

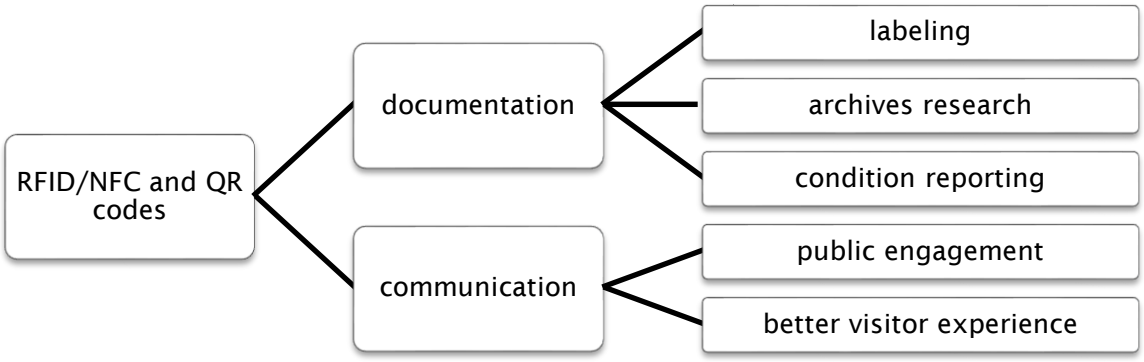
Although it is expected that this data will be of great interest to museum professionals (conservators, curators and objects specialists), the interest of the public in the museum's activities behind the scenes should not be underestimated. Previous experience has already proved that the public is interested in conservation activities, which is illustrated by the success of the exhibition 'In the artefact lab' of the Pennsylvania Museum in the United States, where museum visitors seek to explore the conservation history of objects, either in the open window sessions or via the web site (Penn Museum, 2012). Similarly, the #DigitalInvasions project follows a bottom-up approach asking from members of the public to communicate their experience in Italian museums and sites through the use of web and social media (Invasioni Digitali, 2014).

If AIDC techniques provide data about conservation, they can raise awareness in the public. Such actions support the opening of the museums to the public, in a way that has not been practiced yet to any extent. It is highly likely that the museum visitors will embrace these activities with enthusiasm because they will retrieve data at a depth and a level not comparable to the usual museum visit. Considering the open storeroom visits, these technologies can transform a usual walk around the museums stores to an adventurous exploration of objects, which may not be on display yet, and may never be, because of limited display space. The use of personalised codes can provide overall control of the level of information available to its user, so as to lead to a meaningful interaction between humans and objects, according to their needs.

One of the most challenging applications could be the use of tags during interventive conservation. The development of context aware tags may enable the integration of digital refitting and manual fragment matching, a strategy which is expected to provide optimum results. Although the previously mentioned conservation application of AIDC techniques is possible with the available technology, and without high cost or demand for high level of

expertise, their implementation in remedial treatment requires closer collaboration with experts and maybe technological advancements not yet achieved.

From the above it becomes apparent that the use of codes can contribute to conservation documentation, by improving the way the conservator explores storerooms and archives. The public engagement can be also another benefit from the use of such technologies (Graph 11). In the field of remedial treatment the implementation of tagging is proposed in this thesis, although there are concerns regarding the applicability due to the cost and expertise needed.



Graph 11: The potential of QR and RFID/NFC codes in conservation (Graph author's own).

The following section refers to the use of projections, introduced in section 2.3.4.1.3, which aims to a better visitor experience and is proposed as an alaternative to traditional restoration and interventive treatment.

4.2.2.3 Projections

The Projection Augmented reality can be used as an alternative to conservation operations, by employing either static or dynamic projections. There are restoration operations executed only for aesthetic purposes, such as in painting and retouching. The use of projections instead of actual painting on

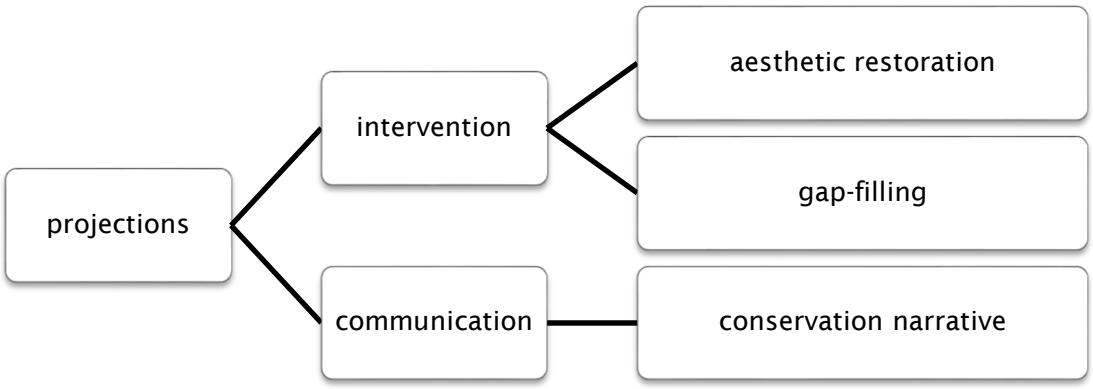
the surface of the object not only succeeds in preserving the aesthetic integrity of the object, but also minimises the operations on the object itself, thus respecting its authenticity.

Sometimes revelation operations, such as cleaning and removal of depositions, are executed only for aesthetic reasons, because these obscuring features need to be removed for the object to be appreciated. Considering that during the manual removal features, either by mechanical or chemical means, there is the danger of removing evidence or altering the appearance of the object unintentionally, these operations are executed in a limited way. Also, in many cases conservators have acquired, by means of digital imaging, the features hidden beyond the visible. Projection of this data on the surface is an alternative to such operations. Considering that the methods are advancing, such an approach may enable future conservators to execute such an operation in a superior way.

In case of incomplete objects, when there is no need for structural support, this approach is an alternative to gap-filling, as the projections can create the illusion of the object being complete. Even if the stability of the object requires the replacement of lost material, the projection can represent the appropriate texture so as to overcome technical problems in the reproduction of the part. Projections, in the case of de- and re-restoration dilemmas, have great potential, as they can provide solutions to the problems of old restorations, which are usually not aesthetically pleasing, and help conservators avoid the risks of de-conservation.

The dynamic, non-static and/or video projections can represent the object at different stages, in order to understand not only its materiality, but also the way it was used. This may include the visualization of the ageing biography of the object under different conditions and alterations during its lifetime, such as over-paintings. For conservation purposes, it will be important to also visualize the appearance of the object as it was discovered, before and after conservation, as well as the different restoration scenarios, in case of opposing hypotheses of its original appearance.

The proposed implementation of projections in conservation are summarised in Graph 12.

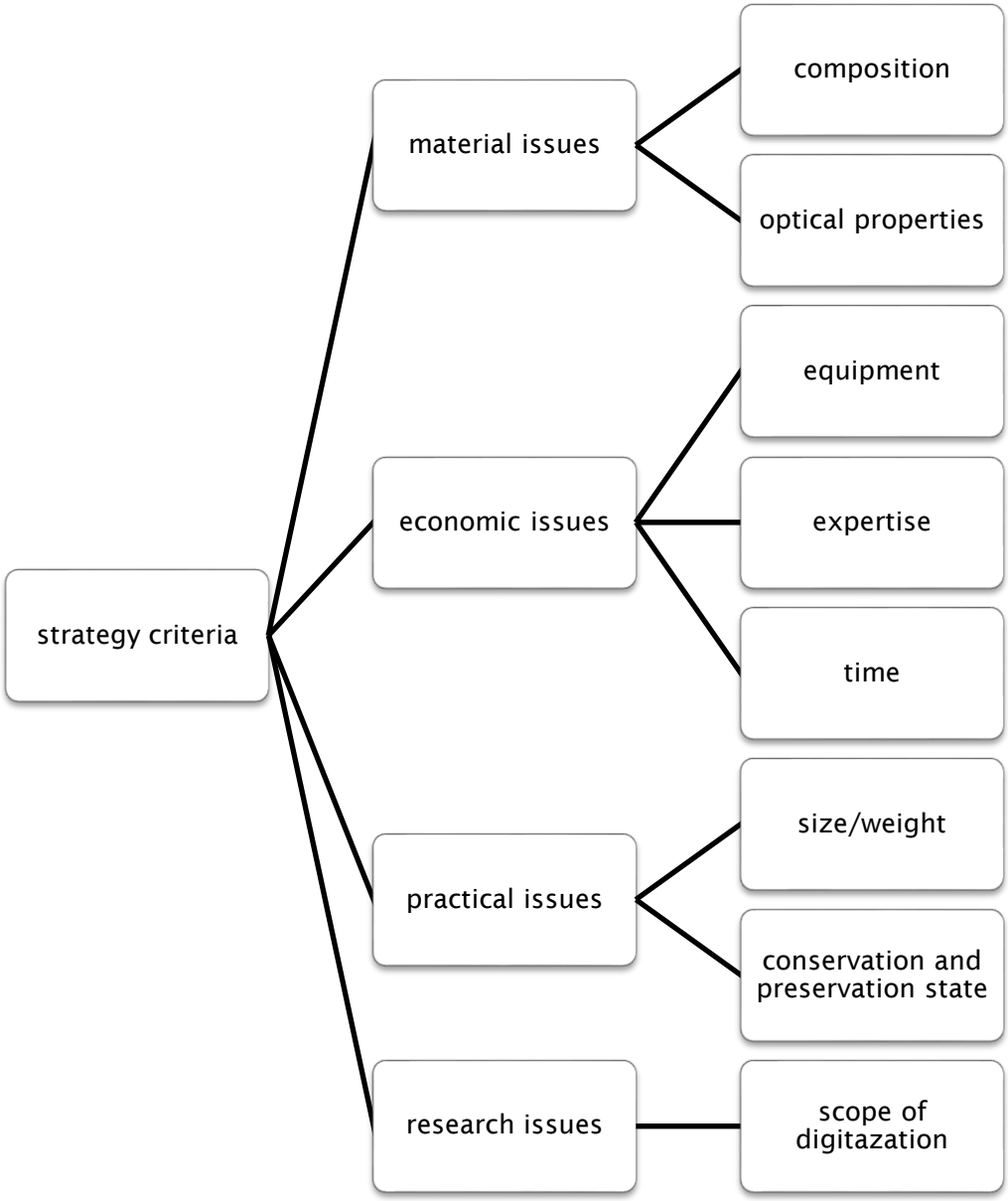


Graph 12: The potential of projections in conservation practice (Graph author's own).

4.3 Digital capture

The field of conservation is undoubtedly one of the most, if not the most, demanding in terms of digital capture techniques, because of the needs for limited human-object interaction, high quality and affordable visualization and analysis. The dilemma of choosing the adequate strategy is obvious, and there is no single answer to that question, considering that the ideal capturing method for each project depends on many parameters, such as the artefact's needs, the expertise of the cultural heritage organization, the time available and required, and the equipment and computational costs (Graph 13).

The digitazation strategy criteria will be analysed in the following sections in an attempt to provide a critique towards digital capture. This is more than necessary nowadays, because the methodologies are developing rapidly and there is a rise in the demand for applications in cultural heritage. Moreover, the differences between them are significant, and dictate the information derived from their application, making it impossible to judge the capture techniques using straight comparative approaches. On the contrary, an attempt to propose successful synergies as well as comparisons, when appropriate, is highly recommended.



Graph 13: Digitization strategy criteria (Graph author's own).

4.3.1 Comparative analysis

The comparative analysis, presented in Table 6, demonstrates the variety of available techniques for digital capture. The most important feature in judging the effectiveness of digital capture techniques is how effective they are for the digitization of various material types. Material properties, including optical properties, such as reflectivity and translucency, as well as chemical properties, such as material type and composition, should be taken into consideration.

Table 6: Comparative analysis of digital capture techniques.

TECHNIQUE	PORTABILITY OF EQUIPMENT	SIZE	TEXTURE ACQUISITION	MATERIAL OF DIGITIZATION
RTI	✓	all	✓	all
HYPER-MULTISPECTRAL IMAGING	✓		No	Primarily objects of complex stratigraphy
X-RADIOGRAPHY	✓	limited	No	Problematic for gold, silver and lead due to opacity to x-rays
CT	No		✓	
NEUTRONS RADIOGRAPHY	✓	limited	No	Problematic for cobalt and silver due to radio-activation
MRI	No		✓	
LASER SCANNING	✓	all	✓	Problematic for highly reflective and translucent materials
PHOTOGRAMMETRY	✓		✓	

4.3.1.1 Material issues

RTI is the most flexible technique of all, as there is no issue, even in the case of reflective and translucent materials, which usually present problems in laser and/or photogrammetric capture. The analysis of objects of complex stratigraphy, which present a combination of materials, may benefit most from the application of multispectral techniques. Radiographic techniques are powerful methods for examination beyond the visible light spectrum, but X-radiography of gold, silver and lead is not recommended due to their opacity to x-rays. Also, the radio-activation of cobalt and silver limits the applications of NR in these materials.

4.3.1.2 Practical issues

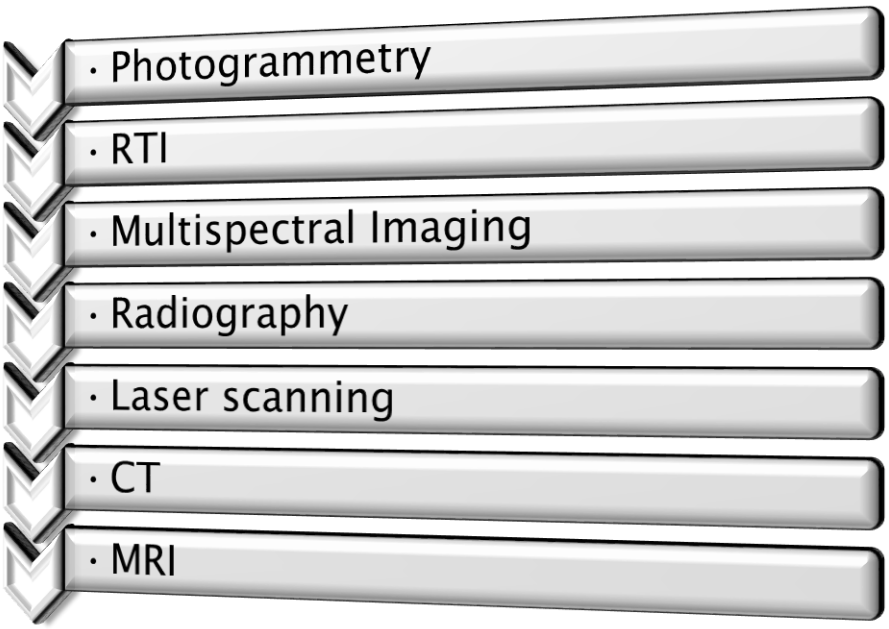
Practical issues, such as the size of the object and the ability to perform capture in situ, need to be considered. One of the main advantages of digital capture techniques, apart from CT and MRI, is the portability of equipment, which is important if the technique is to be implemented in museums, cultural heritage organizations or even in excavations. Although portable tomographic systems have been developed, only a limited number of case studies at an experimental level has been conducted to date. There are no size restrictions for RTI, multispectral imaging, laser scanning and photogrammetry. On the contrary, the size of the object should fit the dome in case of RTI data capture using the dome method. There are some restrictions for radiographic capture, while in the case of CT and MRI not only the size, but also the weight, of the objects should be considered before capture. Another important aspect is the ability of digital techniques to capture the texture of the visualised objects. Radiographic techniques are not effective in texture acquisition. Rather, RTI, laser scanning and photogrammetry can efficiently capture the surface topography, while CT and MRI succeed in capturing the texture of the internal structure of objects.

4.3.1.3 Economic issues

The economic aspects are of great importance for digital capture, including not only the cost, but also the time and expertise needed for capture, processing and interpretation of the results (Graphs 14-16).

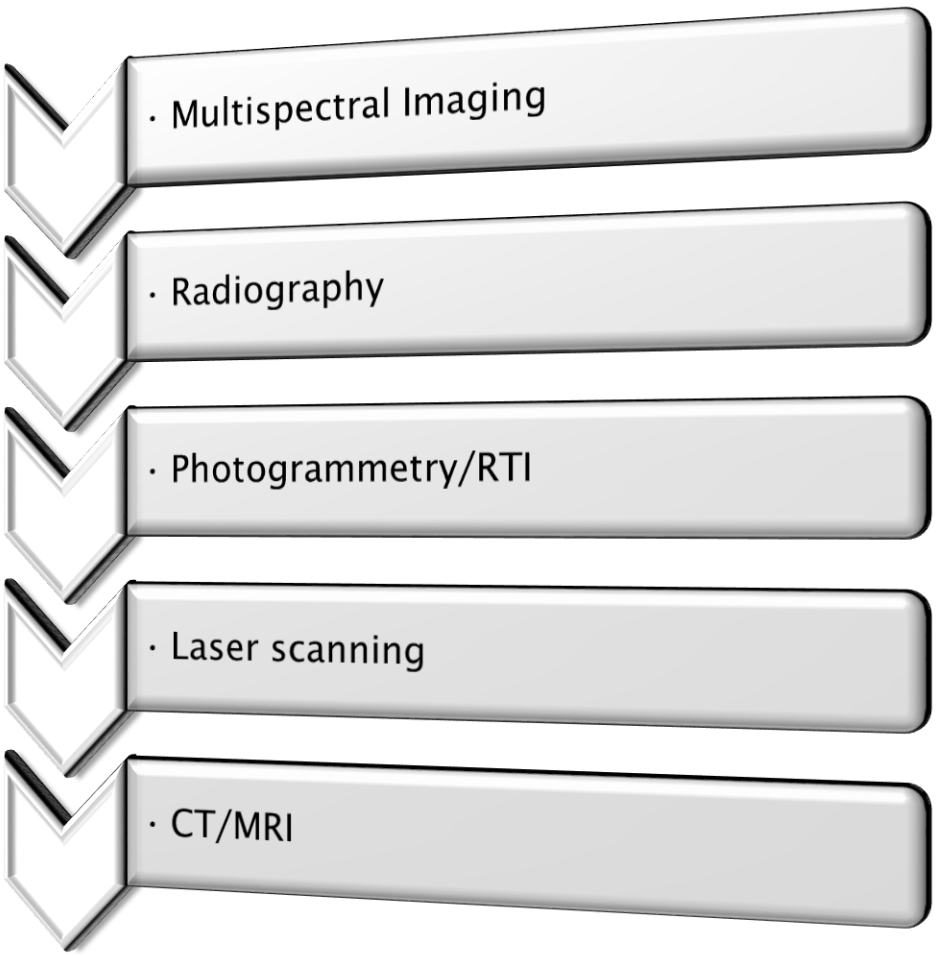
Computational imaging digital capture can be completed easily without previous knowledge thanks to the useful guides available online. Of course experience is valuable and can lead to better results. For multispectral imaging data capture and processing a basic understanding of multispectral cameras and necessary filtration is required. Most conservation training courses include relevant modules. Similarly, for X-radiography systems, the expertise needed is usually covered in conservation courses. For laser scanning specialised knowledge is required for the completion of data capture, due to the equipment involved, and processing of data. Finally, tomographic techniques cannot be completed without the involvement of experts, because the instrumentation for data capture is really complex, and the processing of raw

data requires advanced computer knowledge. Even after the reconstruction, the user needs to know the basics of 3D software so as to effectively examine the models.



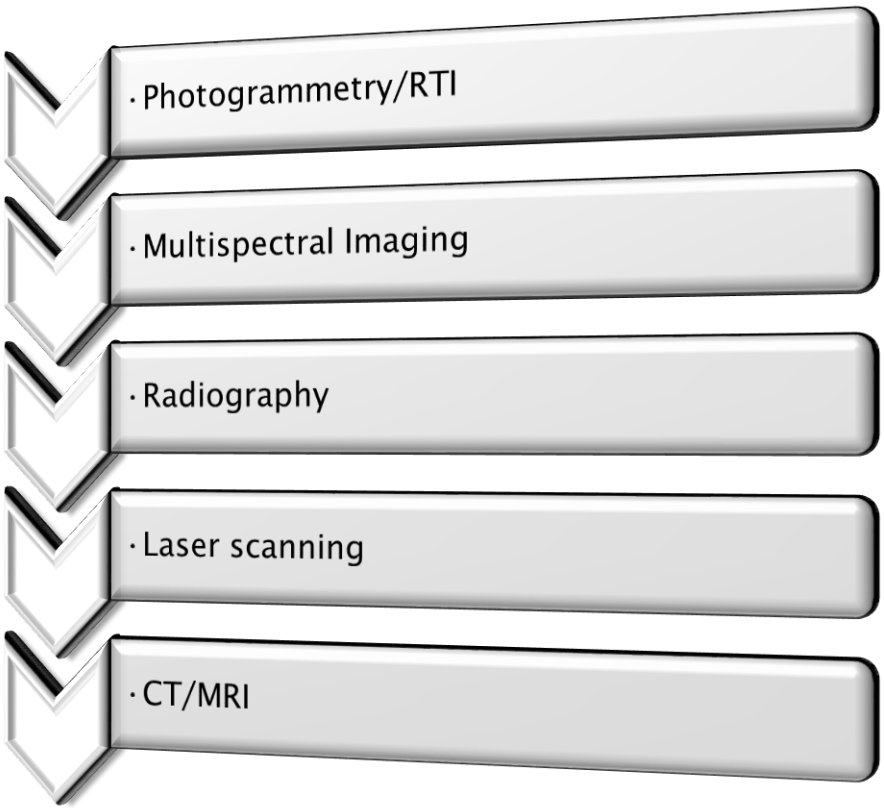
Graph 14: Comparative analysis of digital capture techniques based on the expertise needed for capture, processing and interpretation of the results, from low expertise (top) to high (below) (Graph author's own).

Regarding time, hyper-multispectral imaging, and radiography provide quick results, followed by computational imaging techniques. However laser scanning, CT and MRI are the most time consuming. A typical RTI dataset can be captured, processed and viewed in a couple of hours, or even quicker, depending on the experience of the person capturing the data. For photogrammetry data capture is easy and straightforward, but processing of the dataset can last days, in case of large datasets processed with slow computers. Laser scanning data capture and processing requires even more time. Finally, a typical CT scan takes at least a day, and its processing requires a powerful computer.



Graph 15: Comparative analysis of digital capture techniques based on the time needed for capture and processing, from less (top) to more time consuming (below) (Graph author's own).

The hardware and software costs vary considerably. For photogrammetry standard photographic equipment is necessary. For RTI low cost object can be used as targets. The data capture can be completed with all dslr cameras, but high resolution cameras are preferred. Multispectral imaging techniques and laser scanning are considered techniques of medium cost. Finally, tomographic systems are expensive.



Graph 16: Comparative analysis of digital capture techniques based on the cost for capture and processing, from less (top) to more time consuming (below) (Graph author's own).

4.3.1.4 Direct comparisons

4.3.1.4.1 Raking light and RTI visualization

A comparison of the outcomes of RTI and the photographic documentation techniques demonstrate the impressive capabilities of RTI. Traditional raking light imaging, a well-known and widely used photographic technique for the examination of archaeological objects and works of art, is the predecessor of RTI. This parallel is more than obvious, because the RTI dataset is actually a series of raking light images. Research results indicated that the disadvantages of raking light cannot be overlooked. Raking light examination should not be considered in the case of vulnerable and fragile artefacts, because the handling required for a complete examination contravenes basic

conservation rules and codes of ethics, as it may cause damage. Also, the results are rather disappointing, because of the large number of raking light images needed for a complete examination, and the problems caused by the manipulation and examination of the captured images. No single captured image can demonstrate the characteristic features of archaeological objects, such as three-dimensionality and geometric complexity, in addition to the surface topography of deteriorated material. Also, the specular enhancement capability of RTI viewers can be compared to the specular axial or oblique illumination imaging technique. Moreover, the ability to change the specular parameters in the viewer enables enhanced recording and examination. RTI combines successfully raking and specular illumination imaging techniques. Not only does it record surface anomalies, traditionally captured by specular illumination, but also the depth or height or surface texture, usually documented with RTI.

4.3.1.4.2 Laser scanning and photogrammetry

Although the laser scanning technology is advancing rapidly, having reached high levels of precision, their application for museum conservation purposes is limited due to the high cost of quality equipment. It is true that in terms of geometry the photogrammetric models are not as accurate as laser scanned ones, but the cost and the expertise necessary for laser scanning is much higher than photogrammetry, which provides a cost effective solution to 3d data capture, due to the lower prices of equipment involved in capture, the open source programmes available for data processing, the transportability of the technique, the low level of expertise needed, and the high resolution and colour fidelity in addition to the ease of use.

4.3.1.4.3 X and neutron imaging

By comparing the quantity and variety of applications of x and neutron imaging in archaeology and cultural heritage, one can easily understand the expanded use of the former technique. CT still remains the most commonly used strategy (Michael, 2001; Azhari, 2010). The main reasons for that were the limited accessibility of cultural heritage organizations to neutron sources, the absence of efficient modern neutron imaging equipment and the radio-activation of the object (Rant *et al.*, 2006). It should be noted that nuclear imaging is not as

easily adapted for cultural heritage purposes as x-ray techniques, considering that many cultural heritage institutions have x-ray radiographic equipment in their labs, along with professionals trained to use them. Moreover, the cost of MRI is another limitation for its broader application in cultural heritage.

However, in projects where the applications of X-ray imaging proved to be insufficient, neutron sources provide solutions. Undoubtedly the application of X-ray and neutron imaging in synergy can guarantee the success of a project, due to the many aspects of artefacts studies and conservation that can be explored (Lehmann, 2006). The ability to combine images from photon based and neutron imaging application is a promising technology for future applications (Osterloh *et al*., 2007).

4.3.1.5 Conservation actions & objectives

The critical evaluation of the contribution of the techniques in conservation requires a closer look to the conservation objectives and actions. Table 7 presents a critical evaluation of digital capture techniques according to their contribution in conservation objectives and actions involved in conservation.

- Practicality

In terms of practicality RTI and photogrammetry are considered more valuable because of their ease of use. In particular, the dome RTI methodology enables easy and quick data capture and processing. Similarly, new software for photogrammetric reconstruction offering oprions for relatively fast data capture and processing.

- Communication

All digitazation techniques are useful for communication purposes, but it seems that that RTI, laser scanning and photogrammetry are stronger communication tools, because they are useful to a broader audience, and not strictly to professionals. The virtual artefacts derived from such techniques do not require previous knowledge, making them ideal for public engagement.

- Accessibility

All digital captures technologies transfer artefacts to a more accessible state, either by providing surface, volume, 3d or data beyond the visible.

- Durability and Integrity

Similarly, their contribution in safeguarding integrity and preservation of artefacts is different, but of equal significance, meaning that RTI, laser scanning and photogrammetry are techniques that can be substituted for conventional artefact examination, while data beyond the visible and 3d volume can be substituted for interventive operations. The former group consists of techniques largely considered as examination tools, while the latter refers to investigation techniques. Their contribution depends on the requirements of each conservation project. For example, in the case of cleaning and removal of encrustation and corrosion products RTI, laser scanning and photogrammetry are more useful. In the case of micro-excavations these techniques are not as valuable as radiography, CT and MRI.

Considering the above, in general, computational imaging and laser scanning are common techniques for artefact digitization, and more likely to assist in artefact preservation (durability), while techniques that provide data beyond the visible and 3d data, used mainly for investigation purposes, best safeguard the artefact's integrity.

Table 7: Critical evaluation of digital capture techniques according to their contribution in conservation objectives and actions.

	RTI	**Hyper-multi-spectral**	**radiography**		**Laser scanning**	**Photo-grammetry**	**CT/ MRI**
			x-rays	**Neutron**			
accessibility	Texture and colour data	Data beyond visible			Geometry, texture and colour		3d volume data
durability	✓				✓	✓	
integrity		✓	✓	✓			✓
practicality	✓					✓	
communication	✓				✓	✓	

4.3.2 Proposals for further development of digital capture techniques

Although the field of artefacts digital capture has managed to provide valuable techniques for conservation, there are still undiscovered areas and future developments that can enhance methodological approaches. The goal of this research is to propose affordable and easy to use digital capture methodologies, so as to cover the complexity of artefacts, which present a variety of material types, decorations styles, shape and dimensions. From the literature review one can see that research has been directed to synergistic and comparative approaches between laser scanning and photogrammetry, while the synergies between other digital captures technologies are not as actively explored.

4.3.2.1 RTI

The combination of RTI with transmitted, multispectral imaging and microscopy are areas that should be further exploited in order to use the RTI to its full potential. The proposed techniques, along with their main potential and materials/artefacts types that can primarily benefit from this, are listed in Table 8. RTI synergies are of significant value for visual analysis because they enrich the microscopic, multispectral and transmitted imaging with data about the texture of the objects, assisting in the perception of three-dimensionality, an issue of great importance for the characterization of materials, diagnostic examination and analysis. Microscopic RTI in particular can catalogue the shape and topography of the various components of artefacts at a microscopic scale. Trans illumination and trans irradiation RTI can document structure of translucent materials (paper, canvas), their condition (repairs, abrasions, losses) and painting techniques used. FCIR/FCUV RTI can be useful for simultaneous capture of texture and materials characterization/ differentiation. The list of materials and artefacts types in Table 8 is not explicit, but presents those artefacts that can benefit the most by the application of RTI synergies. The proposed RTI synergies can visualise texture in various spectral areas (multispectral RTIs), using different lighting conditions and magnifications (normal, macroscopic and microscopic RTI), in different conservation states, before, during or after conservation.

Synergistic techniques are expected to contribute in conservation objectives by strengthening the role of digital techniques in terms of the actions involved in conservation, meaning investigation, prevention, intervention and communication. In Chapter 5 the proposed methodologies are trialled and evaluated.

Table 8: RTI synergies.

	RTI dataset	**POTENTIAL**	**MATERIALS /ARTEFACTS TYPES**
Micro RTI	Micro-photographs	To catalogue the shape and topography of the various components of artefacts at a microscopic scale.	all
Trans RTI	Transmitted light images	To document structure of materials(paper, canvas), condition (repairs, abrasions, losses) and painting techniques	Translucent materials, canvas paintings, mounded papyri, photographic material, and works of art on paper or archival material etc.
IR Trans RTI	Transmitted Multispectral images	To reveal texture of hidden features, obscured by linings, mounts of inks and pigments, such as under drawings, inscriptions, watermarks etc.	Artworks on paper, paintings, mounded papyri, archival material etc.
Multis-pectral RTI	Multispectral images	To capture texture of artefacts beyond the visible	Engraved stones in poor conservation condition, restored glass artefacts, painted or engraved ceramics and with encrustations, mortars, painted surfaces, paper and archival material, documentary artefacts
False Colour Multi-spectral RTI	FCIR and/or FCUV images	For simultaneous capture of texture and materials characterization/ differentiation	Painted surfaces, wall paintings, panel paintings, canvas paintings, painted ceramics, paper and archival material, papyrus, parchment,

The proposed techniques will be trialed and evaluated in section 5.3.

4.3.2.2 PG

Three-dimensional digital capture using synergistic methodologies can be further explored. Considering economic and practical issues involved in laser scanning, photogrammetry is considered an area useful research for conservation. Photogrammetry already provides three dimensional data, but its combination with microscopy, and the comparison of the results and combinations with microscopic RTI, can lead to the proposal of the most appropriate methodology for microscopic visual analysis. Other combined photogrammetric approaches, such as 3d multispectral and virtual RTI, although proposed, have not received the necessary attention yet. Limited case studies have been presented. The results of such approaches are not restricted to art diagnostics and visual analysis, but can also assist in treatment proposals, and conservation-restoration intervention. The proposed photogrammetry based synergies are presented in Table 9, as well as the expected outcomes. Computational imaging synergies and laser scanning provide advanced representation of artefacts, and may potentially be powerful communication tools. The proposed techniques will be trialed and evaluated in section 5.4.

Table 9: Photogrammetric synergies.

PROPOSED SYNERGIES	OUTCOME
Multispectral imaging	3d digitization of artefacts beyond the visible
RTI	Enhance 3d digitization quality/ reprocessing of captured data
Laser scanning	Enhance 3d digitization quality
Optical microscopy/ photo-micrographs	3d digitization of microscopic features
Transmitted imaging	3d digitization of artefacts trans illumination properties

The relative absence of synergies between microscopy, RTI, multispectral imaging and photogrammetry should not be considered as gap in the digital capture process, owing to the fact that the vast majority of work presented is focused on visualization. Limited work has been conducted on conservation visual analysis and diagnostic examination. Moreover, the focus is not on treatment proposal and conservation- restoration intervention, with the exception of digital refitting which has been examined more than other applications.

Characteristic examples of such contributions may potentially be those listed in Table 10. Multispectral RTI assists the investigation of artefacts. Microscopic RTI and micro-photogrammetry enhances microscopic examination and preventive conservation. CT/ MRI and virtual RTI contribute in investigation, and may substitute interventive operations.

Table 10: Contribution of synergistic digital capture in conservation practice.

Conservation actions	**Proposed technique**	**Conventional and digital not synergistic approaches**	**Outcome of synergistic approach**	**Conclusion**
investigation	Multispectral RTI	Multispectral imaging RTI	RTI includes textual and spectral information	Added value as an investigation tool
prevention	Microscopic RTI & Photo-grammetry	Optical microscopy RTI	The digital artefact combines microscopic level of detail and advanced perception of three dimensionality	Added value as a preventive conservation measure, less human-object interaction, less handling
intervention	CT & Virtual RTI	x-radiography autopsy RTI	The digital artefact enables virtual autopsies of artefacts	More efficient digital execution of conservation operations
communication	Photo-grammetry & laser scanning & RTI	Photo-grammetry Laser scanning RTI	Enhanced accuracy representation of artefacts	Advanced quality representation for communication purposes

4.3.2.3 Software demands

Besides the further development of digital capture techniques proposed in sections 4.3.2.1 and 4.3.2.2 there is a rise in demand for improved interaction between humans and digital visualizations. The relationship between the human and the virtual artefact, considering the available software, is problematic. The different visualizations conceptually form one entity, and should be examined simultaneously so as to provide better results.

Nowadays one of the working solutions to overlay the images in a dynamic and accessible way is Map Art Viewer, a GIS based specialised software (Carroll *et al.*, 2013) (Figure 103). The IIP MOO Viewer offer more flexibility than image overlay and synchronised viewing, as it enables online publication for high resolution images (Pillay, 2011) (Figure 104). These are useful tools for the virtual examination of digital visualization of static files. Nevertheless, the results of virtual examination of artefacts should be connected to the virtual and the original artefact, considering that all these components form the museum history of the object, which should be easily accessible and available. The best way to achieve this goal is to provide online access to digital files and connections between them and the original artefact.

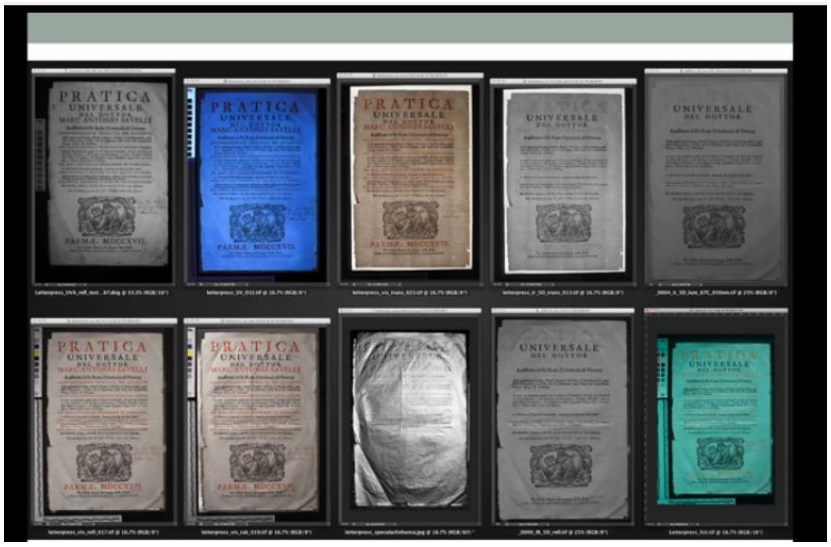


Figure 103: Sceen shot from the Map Art Viewer tware (Carroll et al., 2013). Available from: https://www.youtube.com/watch?v=EJNG-yfe4ko

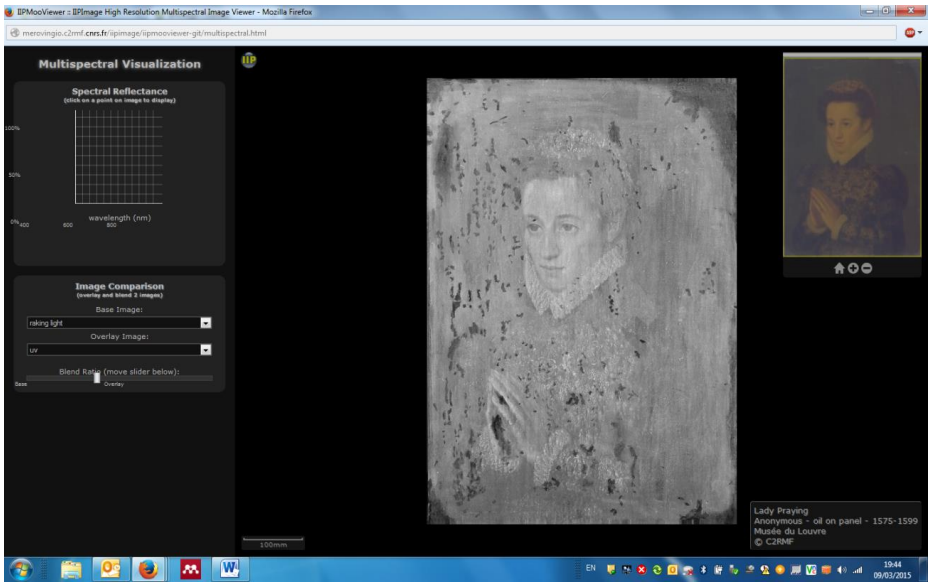


Figure 104: Screen shot from the IIP MOO Viewer. An anonymous 16th Century painting entitled “The Lady Praying”. Louvre Museum. C2RMF. Available from: http://merovingio.c2rmf.cnrs.fr/iipimage/iipmooviewer-git/multispectral.html

4.4 Documentation

In Part one the documentation problems (section 2.2.3) and current approaches (section 2.3.3) are presented, along with an overview of the techniques for digital capture of artefacts (Chapter 3). In the previous section these techniques were critically approached (section 4.3.1) and proposals for new developments (section 4.3.2) were discussed. Apart from the development of advanced visualization methodologies there is the need for their implementation in documentation strategies. The scope of the following sections is to define the role of advanced visualization techniques in conservation (section 4.4.1) and propose useful tools for the systematization of documentation procedures (4.4.2).

4.4.1 3d conservation documentation

The superiority of digital documentation is strengthened by the new capabilities offered to the conservator by virtual reconstruction. The potential uses of virtual reconstruction in the documentation application field are not limited to the visualization of the artefact in its current state. Considering that

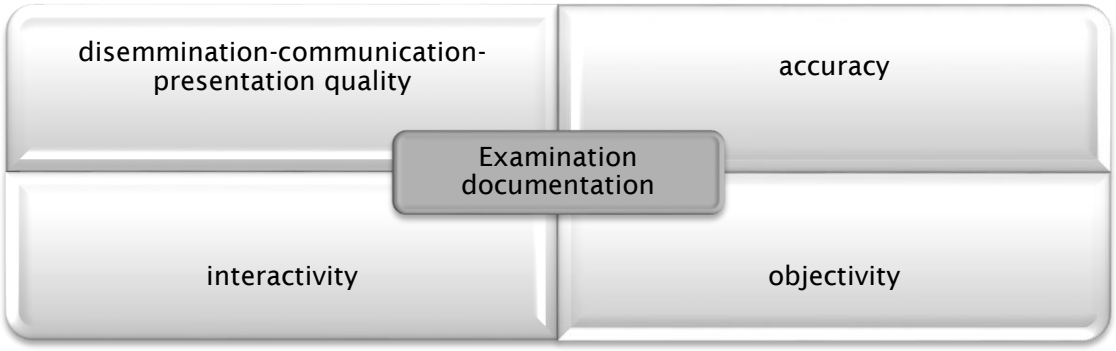
artefacts are subjected to continuous change, three dimensional virtual reconstructions can restore their appearance in previous and future states. A characteristic example of such virtual restoration operations is the virtual repainting of sculptures (Pieraccini *et al.*, 2001; Pintilie, 2011; Beale, 2014). On the other hand, it is also possible to visualise an artefact's future states, when further degradation or restoration operations may take place. These approaches would have been impossible without the contribution of digital technology, because traditional means of archaeological illustration cannot fulfil the needs for photorealistic and physically accurate visualizations in a world of 3d coordinates. It has been argued, with some justification, that the visualization of artefacts in their historical time *'take on a scientific value in its own right, restoring its value as historical testimony to the civilisation'* (Gabellone, 2009, p.114) and that three-dimensional information can be used to present the artwork in a manner that is closer to the artist's intent (Hess and Robson, 2010).

The monitoring of an artefact's state by means of 3d computer graphics is relevant, due to artefacts' unstable nature. The scientific, accurate and carefully planned documentation of the changes introduced to artefacts' appearance, as part of artificial ageing experiments, or as simple condition surveys, can contribute to conservation science knowledge, and drawing conclusions about the development of ageing phenomena and the parameters that affect them.

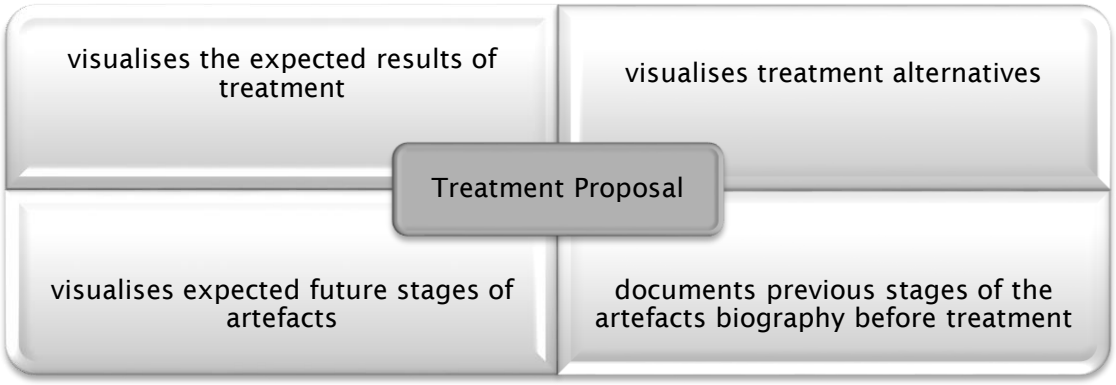
The main advantages of 3d digitization in examination documentation, as shown in Graph 17, are the improved dissemination of records, an advanced level of accuracy, as well as the objectivity and the interactivity introduced by the 3d models in the examination documentation. The potentials of integrating 3d digitization and virtual reconstruction in treatment proposal are presented in Graph 18. The range of new possibilities with the visualization of the expected results of treatment, and the treatment alternatives, can lead to improved decision making, while the visualization of future and previous stages of the artefact make possible the documentation of the artefacts biography, in a way superior to traditional approaches. In the case of treatment documentation 3d digitization and virtual reconstruction can visualise, in a more meaningful way, the alterations introduced to the object, along with any

necessary additional information in the form of annotations. It appears that the contribution of 3d digital documentation is of less importance in the case of preventive conservation documentation, as the advantages do not refer to the quality of the actual documentation, but to the systematization of data. This is not a trivial point, but it cannot be compared to the outcomes of the digital documentation of examination, treatment proposal and treatment.

The use of RTI as a tool to document treatment and monitor the conservation state is presented in chapter 5. The documentation of digital and manual refiting, virtual reconstruction is presented in chapter 6.



Graph 17: The main advantages of 3d digitisation in examination documentation (Graph author's own).



Graph 18: Uses of virtual reconstruction in treatment proposal documentation (Graph author's own).

4.4.2 Scientific workflows and systematic conservation documentation

Following the discussion in section 2.3.3.2 improved workflows can benefit conservation methodology, following the example of other disciplines, such as

chemistry, where digital data and physical samples are basic components of research. This thesis argues that the expansion of digital technology opens new perspectives in conservation research and practice. Scientific workflows can support conservation operations, and above all, their contribution is vital in the area of documentation. The workflows, such as the Open Provenance Graphs, can act as guidelines for the appropriate implementation of methodologies. In order to contribute in conservation OPM Graphs should be in accordance with policy documents for conservation-restoration and reflect the ideas of the existing Charters and best practice guides, use precise scientific terminology, and incorporate a high level of technical knowledge related to conservation operations. For example, OPM Graphs for conservation processes can be found on Appendix A1.

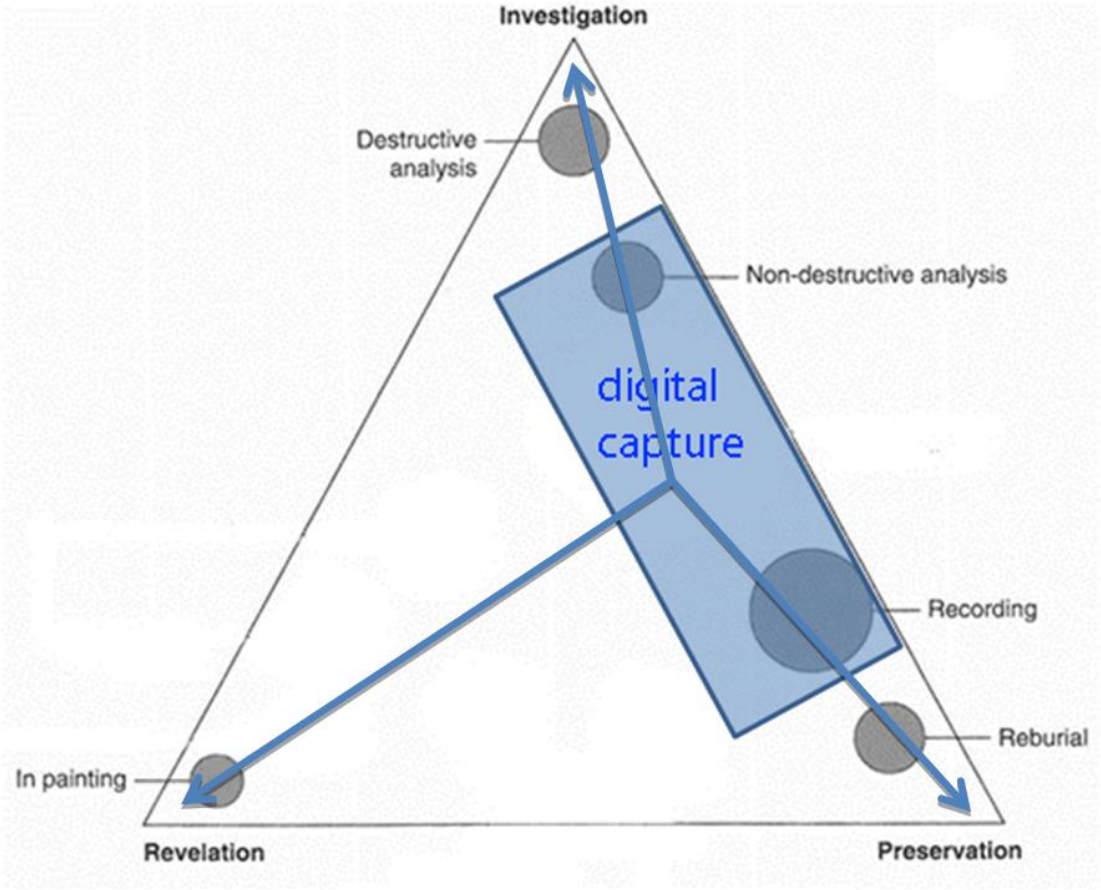
In particular, in case of relatively new and not yet established digital techniques, workflows can be a valuable tool and take the role of master plans for conservation laboratories. The successful implementation of the methodologies includes expertise that goes beyond traditional conservation training. For that reason, the successful documentation of processes involved in conservation virtualization, and furthermore their dissemination in a meaningful way, are issues of crucial importance for their further development and broader appreciation within the conservation community. Considering the above, the proposed methodologies in the following chapters are accompanied by systematic documentation that takes the form of OPM graphs.

4.5 Reflections on conservation theory

This chapter a list of proposals for further developments of digital capture and documentation approaches have been presented, along with a discussion on interrelationships between physical and virtual artefacts. These ideas are new for the field of conservation and there is a clear need for trial and evaluation, which will be the focus of Chapters 5 and 6. Simultaneously, the exploration of their relevance to conservation theory and the interrelationships formed between traditional approaches, new digital techniques and conservation objectives is also a necessity.

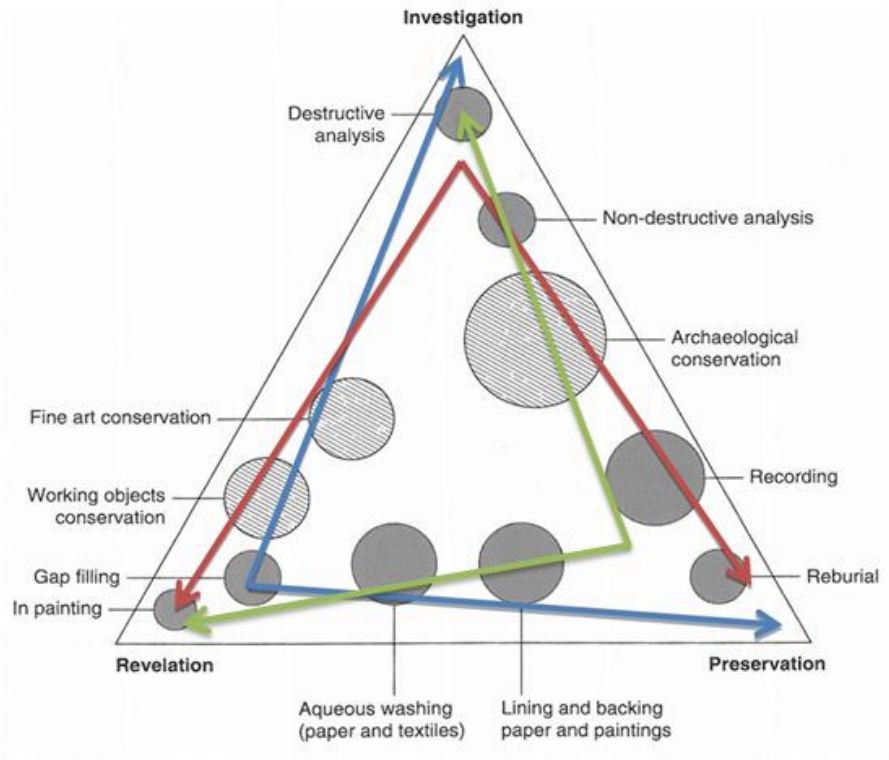
One of the most efficient methods to describe and represent visually the main concepts of conservation is the RIP (Revelation-Investigation-Preservation) balance diagram, a triadic graph which presents the aims of conservation by incorporating its three opposing goals; revelation, investigation and preservation (Caple, 2000). The original mapping of RIP balance diagram, as proposed by Caple (2000), includes main conservation actions, such as recording, non-destructive and destructive analysis, gap filling, in painting and recording as well as the basic conservation sub disciplines, those of archaeological and fine art conservation. In each corner of the triangle an extreme conservation action is located; the destructive analysis for investigation, reburial for preservation and in painting for the revelation. Actions of less extreme character are located in the space between these extremes. In that way complex conservation actions are expressed visually in a systematic and comprehensible way. The RIP triadic graph offers the opportunity to the conservator to describe the whole conservation process as well as all the individual actions carried out. The absence of numerical scales or absolute values should not be considered as a disadvantage, because the diagram seeks to identify the interrelationships formed between the various conservation actions. Kemp (2009) reasonably states that this schema represents the dynamics in designing and executing conservation actions, with each corner being a core idea in conservation methodology. For these reasons the RIP triadic graph offers the opportunity to discuss the role of digital techniques in conservation practice, express their potential and relate them to traditional-conventional practices in an effective and comprehensible way.

The mapping of digital capture techniques in the RIP triangle is presented in Graph 19. While conventional recording covers an area between preservation and investigation, the mapping of the application of digital capture techniques covers an expanded area, which includes non-destructive analysis and recording. Digital capture techniques assist in revelation, due to their ability to reveal features of artefacts without sacrificing material and aesthetic integrity, acting at the same time as preventive conservation measures, while the opportunity to perform more effective artefact analysis than traditional techniques is provided.

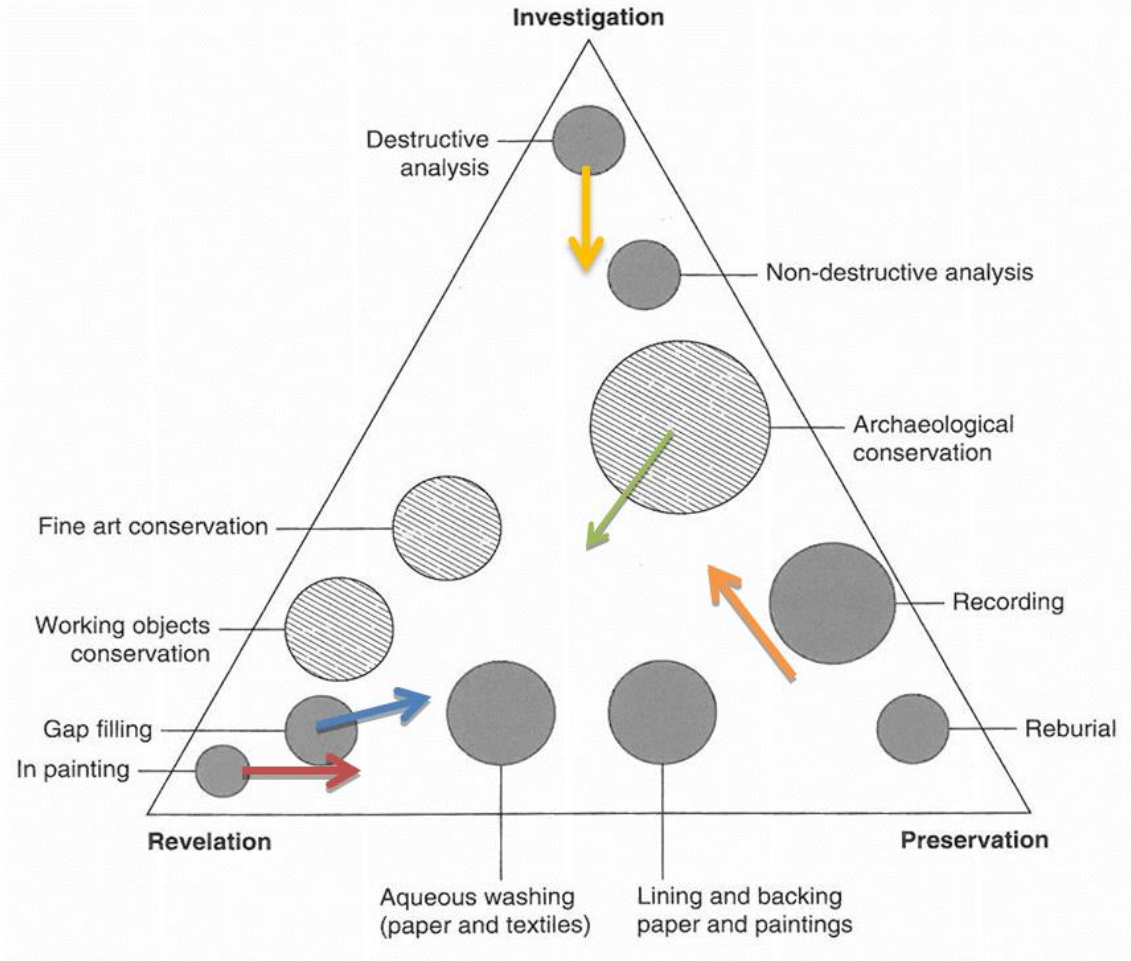


Graph 19: The RIP diagram (Caple, 2000, p.34). New mapping of digital capture techniques (Graph author's own).

As shown in the Graph 20, the digital solutions proposed alter the dynamics of conservation actions. While traditional approaches towards restoration are mapped closer to the revelation corner, the execution of these operations using 3d digitization, modelling and 3d printing are forced towards the investigation and preservation corner, due to their research potential and their efficiency as preventive conservation measures (blue arrows). Conventional investigative cleaning and relevant destructive operations are mapped close to the investigation corner, which are moved towards the revelation and preservation corners if executed virtually (red arrows). In general digital analogues to traditional operations, as represented in the Graph 21, tend to avoid extremes and manage to balance between and contribute to the core ideas of conservation.



Graph 20: The RIP diagram (Caple, 2000, p.34). New mapping of digital restoration (blue arrows), virtual investigation techniques (red arrows) and digitization (green arrows) (Graph author's own).



Graph 21: The RIP diagram (Caple, 2000, p.34). New mapping of digital applications in conservation practice. Orange: 3d replication methodologies as an alternative to moulding and casting. Red: projections as an alternative to aesthetic restoration operations. Green: virtual conservation and/or digitally enhanced conservation operations. Blue: 3d printed detachable fills. Yellow: not destructive virtual investigation techniques (Graph author's own).

4.6 Summary

In this chapter the interrelationships between physical and digital artefacts, as well as mixed reality approaches, were discussed. Also, a comparative analysis of digital capture techniques, and proposals for their further development and documentation, aiming at virtual visual analysis, were presented. A reflection on these novel methodologies in conservation theory was presented, leading to new mappings of RIP schemas. These proposals will be trialed and evaluated in the following chapters.

Chapter 5: Virtual visual analysis

5.1 Introduction

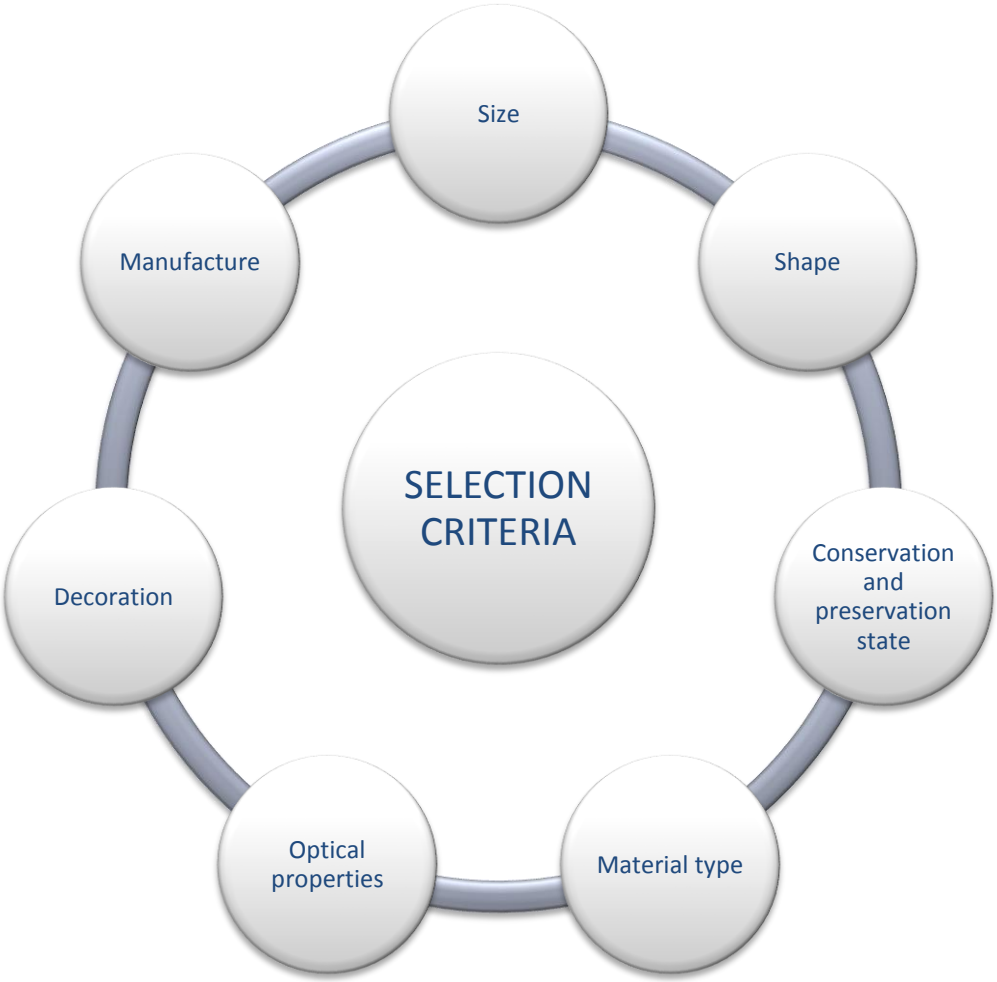
The purpose of this chapter is to evaluate the efficiency of RTI and PG in meeting conservation objectives, with particular emphasis on conservation visual analysis. Although these techniques are increasingly being used in conservation, the lack of evaluation studies limits their research potential. The research question is whether the use of these techniques enhances our understanding of artefacts and facilitates virtual visual analysis. In order to achieve this goal a novel evaluation methodology has been developed, based on key aspects of conventional conservation methodology.

In addition, integrated RTI and PG methodologies have been developed, focused mainly on the synergy of RTI and PG with microscopy, multispectral and transmitted imaging techniques, so as to meet conservation needs for limited human-object interaction, high quality and affordable visual analysis, microscopic levels of detail and advanced documentation. These methodologies were tested in an attempt to provide complementary enhanced visualizations. One of the most obvious conservation needs, identified even in the earlier stages of this research, was the microscopic level of detail required for conservation, considering that microscopic lenses are considered as an extension of the conservator's eyes. The applicability, practicality, and efficiency of microscopic RTI and PG approaches need to be tested. Similarly, the multispectral imaging techniques, largely used for visual analysis of artefacts, were applied in RTI and PG methodologies in order to investigate whether the combination of technologies leads to more efficient digital capture, and present new possibilities for research.

The application of the proposed methodologies on a variety of material and artefacts types aims at defining the potential of RTI and PG in respect to the decay, use and manufacture evidence of each specific group. Of particular interest is the experimental RTI capture of coins before, after and during conservation, in an attempt to test the efficiency of RTI as a conservation monitoring and treatment documentation tool.

5.2 Selection criteria

The case studies were selected based on general criteria, such as dimensions, geometry, conservation and preservation state, in an attempt to cover a variety of different material types and optical properties (Graph 22). In that sense objects with different decoration and manufacture techniques were captured.



Graph 22: Study material selection criteria (Graph author's own).

For the evaluation of RTI in archaeological materials recording and examination, artefacts from the Derveni Tombs were selected. The Derveni Tombs, discovered in 1962, are considered to be one of the most significant archaeological sites in Northern Greece because of the numerous rich grave

offerings and the important location in the ancient Mygdonian city of Lete, on the pass of Via Egnatia. The cemetery consists of seven graves, and according to the excavation publication is dated back to 320-300 or 310-290 BC. They present a variety of types of artefacts, including vases and vessels, weapons, harness equipment, sport and training objects, furniture, jewellery, cosmetics, figurines, toys and a limited number of coins (Themelis and Touratsoglou, 1997). The whole collection is either exhibited or stored in the Archaeological Museum of Thessaloniki, in stable and controlled environmental conditions. According to the archive of the museums' conservation department the grave offerings were cleaned with water, recorded, grouped and joined just after excavation in 1962. Re-conservation on part of the collection took place during the '80s and the '90s. This study provides an overview of RTI in the study of artefacts, owing to the fact that the Derveni cemetery presents an exceptional range of various material and artefacts types, in different conservation and preservation states.

In tombs A, D, B and E of the Derveni cemetery a large number of alabaster alabastra, elongated, narrow-necked flasks, with rounded bases and broad rims, were discovered in a variety of sizes, either complete or in fragmentary state (Themelis and Touratsoglou, 1997) (Figure 105). Capturing fragments of alabaster alabastra and complete vessels offers the opportunity to evaluate the efficiency of RTI and microscopic RTI in conservation examination. Another interesting feature is the detection of tool marks and other manufacture evidence using RTI, considering the published work on experimental studies regarding the making of stone vessels (Stocks, 1993; Vargiolu *et al.*, 2007) which indicates that their production consists of the following steps: shaping of the rock with stone and metal tools, marking the position of drilling, core drilling and boring the interior and polishing the exterior (Hodges, 1976; Hood, 1994) (section 5.3.2.2.1).

Figure 105: Alabaster alabasta from Derveni Tomb B. Photograph from the Archive of the Archaeological Museum of Thessaloniki.

For glass the decision to capture two glass core-formed alabastra of dark blue glass, decorated with a dense feather pattern in white, blue and yellow, with dulled surface and restoration areas, was based on their poor state of preservation, which required an advanced level of recording (Figures 106-107). Moreover, the detection of manufacture evidence is particularly interesting in this artefact type because of the different scenarios that have been discussed by researchers. Ignatiadou (2009) states that the use of granulated glass results in a glass material with different properties; full of hundreds air bubbles and translucent. These results would have been impossible using other proposed techniques. Moreover, the air bubbles act as initial points for material degradation. The initial pitting phenomenon is expanded; the glass material loses its cohesion and stability, due to mineralisation, resulting in powdering and fracture. The application of RTI can potentially shed light on the making of these vessels and confirm or reject the manufacture sequence mentioned above (5.3.2.2.2).

Figure 106: Glass alabastra from Derveni Tomb A. From left to right, A44 height: 0.123m., A45 height 0.127m., A46 height 0.132m. Archaeological Museum of Thessaloniki. (Grammenos, 2004, p.240).

Figure 107: Core-formed alabastra of dark blue glass, decorated with dense feather pattern in white, blue and yellow from Derveni Tomb D. D31 height: 0.089m. (left), D32 height 0.102m. (right). Archaeological Museum of Thessaloniki. (Image author's own

Wall painting fragments with colour decoration were discovered in tombs B and Z. The walls of the chamber of tomb B were coated with two colours of lime plaster in two zones of equal width (0.80 m). The lower zone was red and the upper white, decorated with a continuous guilloche of olive branches with blue-red leaves and black berries. Tomb Z, a pit grave, was plastered on the inside (Themelis and Touratsoglou, 1997). The wall painting fragments selection for the purposes of this study was based on their different level of preservation and the colour variation (Figure 108) (section 5.3.2.2.3).

Figure 108: Wall painting fragment from Derveni Tomb Z. Length 0.077m. (left) and small wall painting fragment from Derveni Tomb B. Archaeological (right) Museum of Thessaloniki (Image author's own).

The study devoted particular attention to ceramic vessels, where different conservation states - fragmented, complete and restored vessels - were included, as well as vessels with varying decoration (section 5.3.2.2.4). The West Slope vessels, named after the large amount of over-painted pottery found on the West Slope of the Acropolis, have a characteristic painted and incised decoration on the black glazed background, and were used throughout the eastern Mediterranean during the Hellenistic era. Capturing at macroscopic and microscopic level fragments of west slope wares can provide a solution to dating problems discussed in the literature. As proposed by Rotroff (1991), the study of the decoration is key for refining chronology. In such an approach the poor state of preservation, not only due to common degradation but also because of the nature of West Slope painting, is problematic. The flaking of the painted designs, and sometimes of the entire decoration, is a common

phenomenon. Another feature that needs to be revisited using RTI is the use of relatively thick colour for the yellow-tan details, which in comparison to the white is obvious, discussed by Cook (1997) in his study of Greek vase painting (Figure 109).

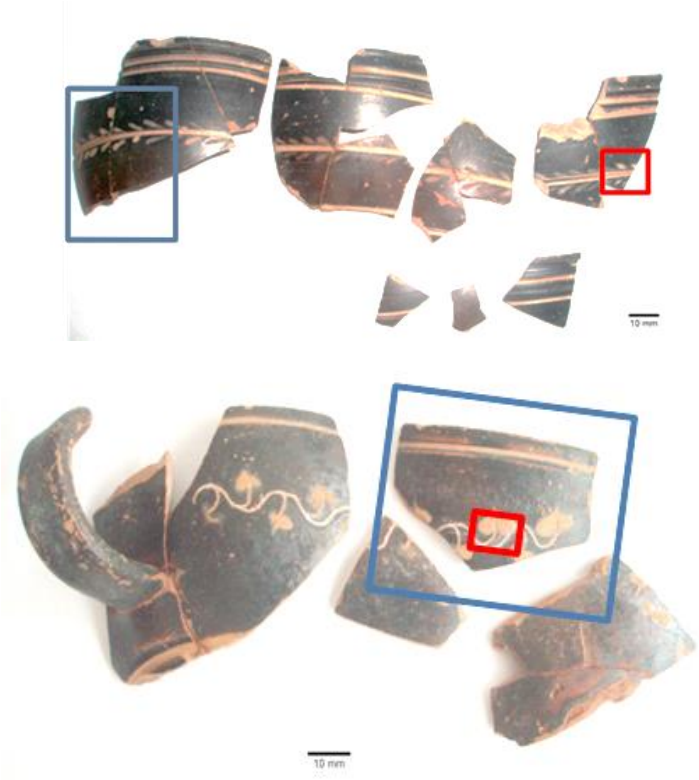


Figure 109: Fragments of west slope vessel from Derveni Tomb C. Archaeological Museum of Thessaloniki. The rectangles demonstrate the areas for macro and microscopic RTI captures (Image author's own).

Vase, vessels or fragments of red-figure, gnathian (Figure 110) and Faenza maiolica tin-glazed wares (Figure 111) were examined, so as to evaluate the application of RTI to different painting techniques and styles. The red-figure pelike (storage-jar) H2 (Figure 112) is attributed to the Painter of the Wedding Procession, and the scene is visible, although the surface shows discolouration, stain, salt efflorescence, colour loss, gaps and pits. On the contrary, in the case of the pelike C1 (Figure 113), attributed to the group G, the scene is indiscernible, because of the overall poor state of conservation, the large restored areas and the highly deteriorated surface with a large amount of colour loss. The characteristic features of red-figure vases are not easily detected using traditional documentation and recording methodologies. Cook (1997) noticed this deficiency, and in particular the fact that the relief lines are

not evident in usual archaeological reproductions. Corbett (1965, p.21) clearly states that '*it is impossible to light the vase so that all parts of the sketch show clearly at the same time*'. Specular and raking light photographing techniques have been proposed in order to successfully represent the surface variations (Clark *et al*., 2002; Corbett, 1965). An incomplete gnathian skyphos of unknown provenance from the archaeological collection of the University of Southampton is also included in this study. It is put together from fragments, and the application of multispectral RTI is of interest so as to evaluate its efficiency in the examination of previous repairs. In addition, fragments of Faenza maiolica jugs in different preservation states were captured, in an attempt to test the ability of RTI in condition reporting and examination of tin-glazed wares.

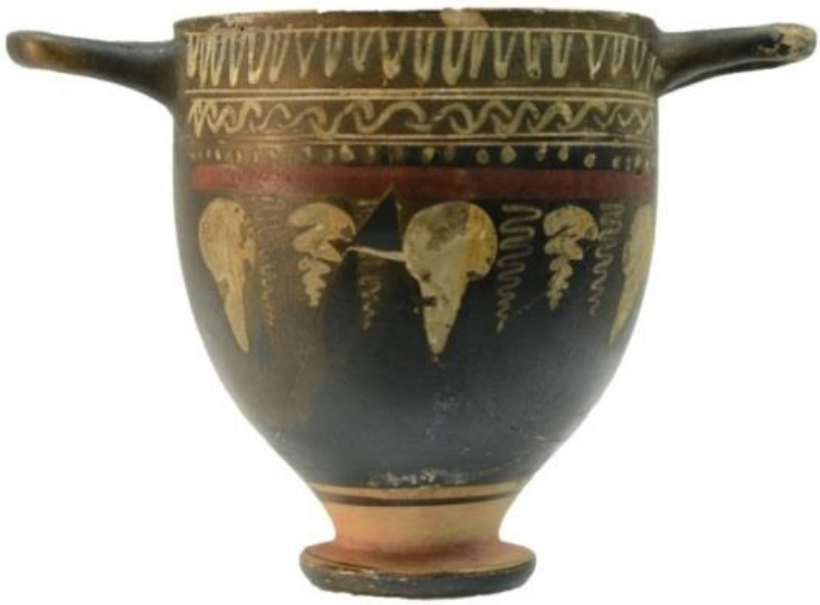


Figure 110: Gnathian skyphos. Height 8.5cm. University of Southampton Archaeological Collection. (Image author's own).

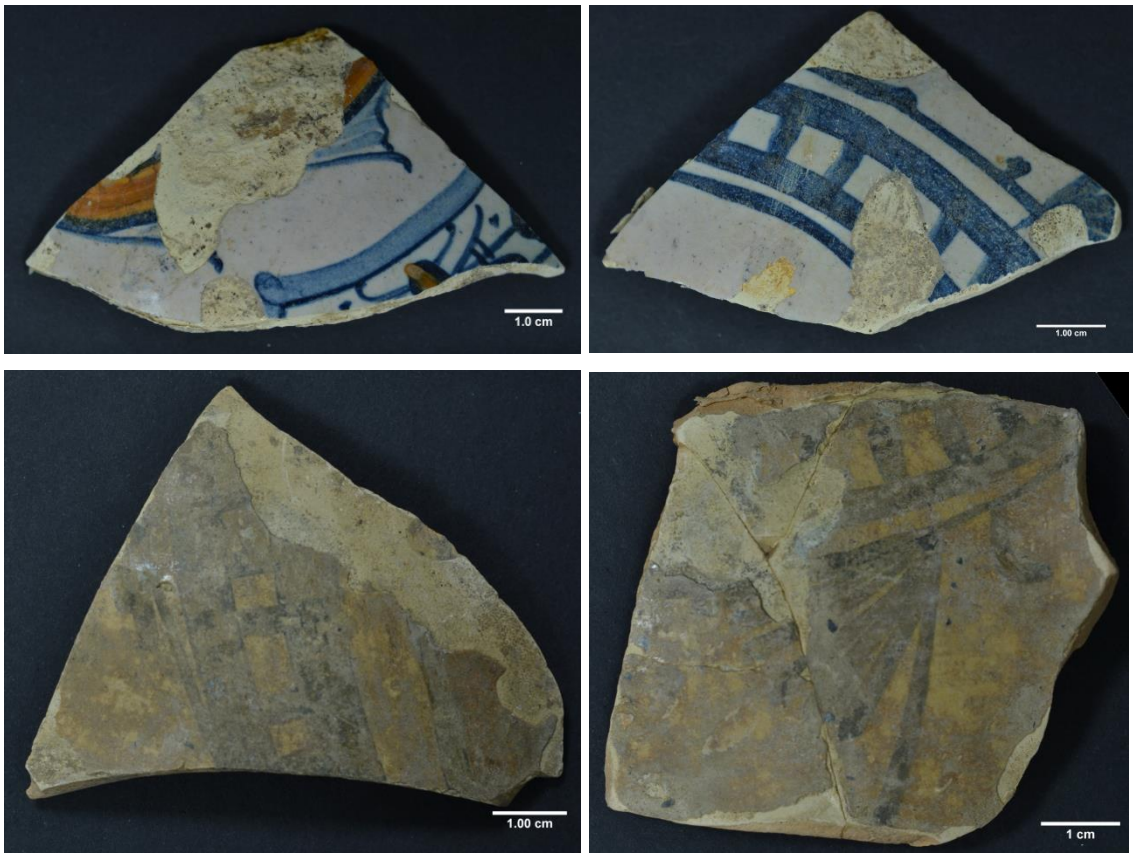


Figure 111: Faenza maiolica fragments from jug 366 (top) and 367 (below). Southampton City Council Archaeological Collection (Image author's own).

Figure 112: Red figure pelikes H2, Derveni Tombs. Height 0.030 m. Archaeological Museum of Thessaloniki (Image author's own).

Figure 113: Red figure pelikes C1, Derveni Tombs. Height 0.255 m. Archaeological Museum of Thessaloniki (Image author's own).

Apart from vases and vessels, other types of ceramics were used as a case study. A characteristic example is the group of gilded and/or painted ceramic roundels with the head of Athena Parthenos, discovered in Tomb B (Figure 114). The different decoration styles, either painted or gold gilded, and states of preservation, in addition to their small size (diameter 0,022m) makes them an appropriate case study for the macro and microscopic RTI evaluation.

Figure 114: Group of gilded and/or painted ceramic roundels with the head of Athena Parthenos, from Derveni Tomb B. Archaeological Museum of Thessaloniki (Image author's own).

Organics form a very demanding material group in conservation, and as a result objects made of wood, leather (Figure 115), skeletal material (Figure 116), and a fragment of the Derveni papyrus (Figure 117), are included in this study as well (section 5.3.2.2.5). Also, capturing composite objects is another area of interest, where degradation effects such as the mineralization and replacement of organic material can be analysed via RTI visualizations.

Figure 115: Leather fragments with textile imprints (B109) (left) and burnt leather fragment with holes at serial arrangement for sewing (right) (A21). Derveni Tombs. Archaeological Museum of Thessaloniki (Image author's own).

Figure 116: Incised ivory plaques fragments. Detail of Eros with remnants of colour blue and red decoration (E7a) (left) and detail of woman's clothing with remnants of red colour (E8b) (right). Derveni Tombs. Archaeological Museum of Thessaloniki (Image author's own).

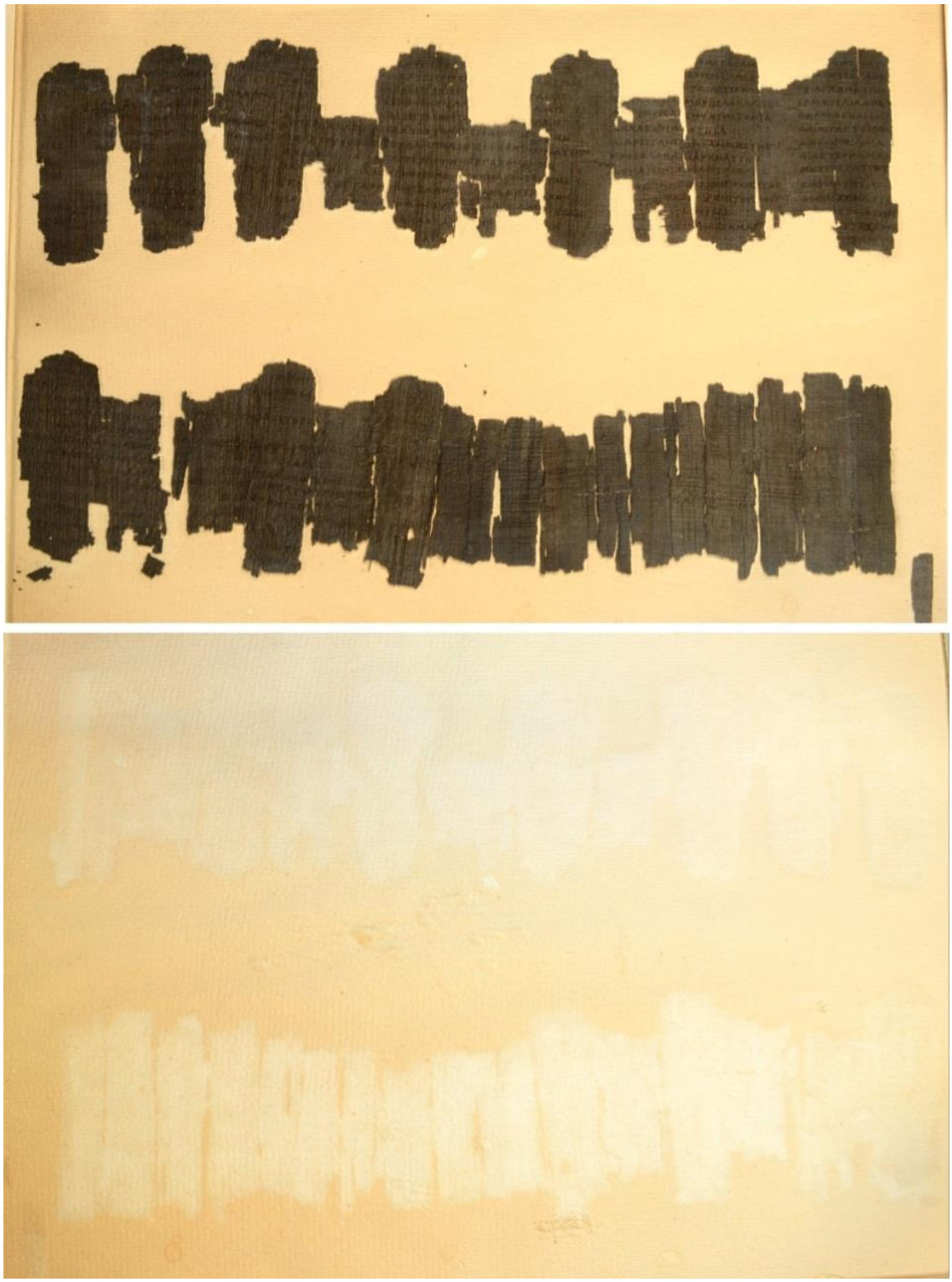


Figure 117: The Derveni Papyrus fragments, digital images, recto (top) verso (below). Archaeological Museum of Thessaloniki (Image author's own).

In the case of metal objects, a variety of materials was tested, including objects made of bronze, iron, silver and gold, so as to present a variety of different optical properties and corrosion phenomena (Figure 118) (section 5.3.2.2.6). Of particular interest was the evaluation of RTI in numismatics, focused on examination, conservation documentation, identification and preventive conservation because of their small size and the low relief detail. For the purposes of this case study, ancient Greek and Roman coins were selected for further investigation and cleaning monitoring (section 5.3.2.3).

Figure 118: Leather attached to a copper alloy ring (top left).Fragments of bronze mirror (Z32) diam. 5cm (top right). Knife, length 0.24m (B106) (middle). Gold gilded silver sheet in the shape of shield with scene of a Macedonian shield, diam. 0.036m. (A19) (below). Derveni Tombs. Archaeological Museum of Thessaloniki (Image author's own).

Oil paintings and wood painted panels, as well as colour testers, were used to assess the infrared and transmitted imaging, along with RTI (section 5.3.2.1). Considering the efficiency of transmitted imaging in canvas paintings, examination of a selection of canvas testers and two paintings were used as a case study for the transmitted RTI experimentation. Painted panels are the most appropriate study material for initial experimentation for the development of a multispectral RTI diagnostic methodology, as previous work has proved the benefits of multispectral examination on paintings, due to their interesting stratigraphy. The application of RTI in icons is a promising area of research, because icons present interesting surface topographies, which are difficult to capture and examine using conventional methods, due to their planar shape and their reduced three-dimensional characteristics, along with the gold or silver gilded areas. Moreover, icons layering structure, as well as the interesting colour palette used by artists, can stimulate those using RTI technology to create methodological innovations. It is also notable that RTI can be an excellent addition to the icons' examination protocol, which has developed via thorough research, either destructively, using analytical methods (Raman spectroscopy, SEM-EDX, GC-MS) or preferably non-destructively (optical microscopy, multi-spectral imaging, X-radiography, computer aided tomography, XRF). Nevertheless, icons are an artefact type which has received minimal attention with RTI applications. Zányi (2007) underlined the inefficiency of photography or active 3D range scanning in capturing gold, silver leafs and tempera painting technique of icons. Their case study of the apse mosaic at the Angeloktisti Church at Kiti, Cyprus, although it did not include experimentation on icons, highlighted the efficiency of RTI in capturing gold, silver and glass tesserae, providing an advanced perception and enabling explorations of the various different views of the mosaic

The icons used in this study are modern replicas, created using the traditional materials and techniques of Byzantine egg-tempera painting, as well as oil paintings on canvas (for a discussion about the use of replicas in conservation research see Appendix B). The use of replicas and testers is entirely reasonable for the purposes of the present research from an ethical perspective. Although the methodologies consist entirely of non-destructive techniques, the initial testing of the proposed methodologies in replicas is an ethical and respectful approach towards original artefacts. Hence, unnecessary manipulation of

authentic artefacts is avoided, minimising, in that way, the risks. Also, in practical terms, this approach offers the opportunity for unlimited capture tests in a more controlled environment than the museum lab, and as a result provides the necessary data for the development of an improved diagnostic methodology. Considering museum policies, the limited time provided with access to the authentic artefacts, especially in case of the artefacts on display, as well as the geographical distribution of authentic artefacts used as case studies, the use of replicas is considered a valuable addition to the present research.

A series of purpose build testers were included in this study, enabling us to discuss the major issue of over painting. Each layer was painted with a certain stroke direction, horizontal, vertical and diagonal. Hence each layer's texture is differentiated. Moreover, the response to IR radiation of each pigment differs, from a transparent pigment in the 2nd layer to a totally opaque one in the 4th layer. This situation presents a growing level of difficulty for transmitted IR radiation and RTI. Table 11 presents the stratigraphy of canvas testers.

Table 11: The stratigraphy of canvas testers.

Tester No	*1st layer*	*2nd layer*	*3rd layer*	*4th layer*
1	RTI written in carbon black	Cadmium red – horizontal painting strokes	Cement green – vertical painting strokes	Raw ombre – diagonal painting strokes
2				-
3			-	-

For PG reconstruction artefacts of different optical properties were selected. Ceramics with different reflectivity have been selected, such as a coarse ware ceramic fragment from a neopunic amphora, and a painted geometric kantharos, glack glazed gnathian pottery vessels with painted and incised decoration (Figures 119-120), so as to define the efficiency of PG as a 3d digitization technique. The translucent monochrome glass vessel, the highly reflective silver coin and the bronze fragments and the stone objects, whose surfaces present different levels of reflectivity, were also captured to fulfil this

goal. Further to this, objects with different shapes and level of geometric complexity have been used, as well as objects which present a variety of degradation phenomena and are in different preservation state (section 0).

Figure 119: Ceramic vessels. Gnathian chous (left) black glazed chous without handle (right). The archaeological Collection of the University of Southampton (Image author's own).

Figure 120: Geometric kantharos. The archaeological Collection of the University of Southampton (Image author's own).

5.3 RTI

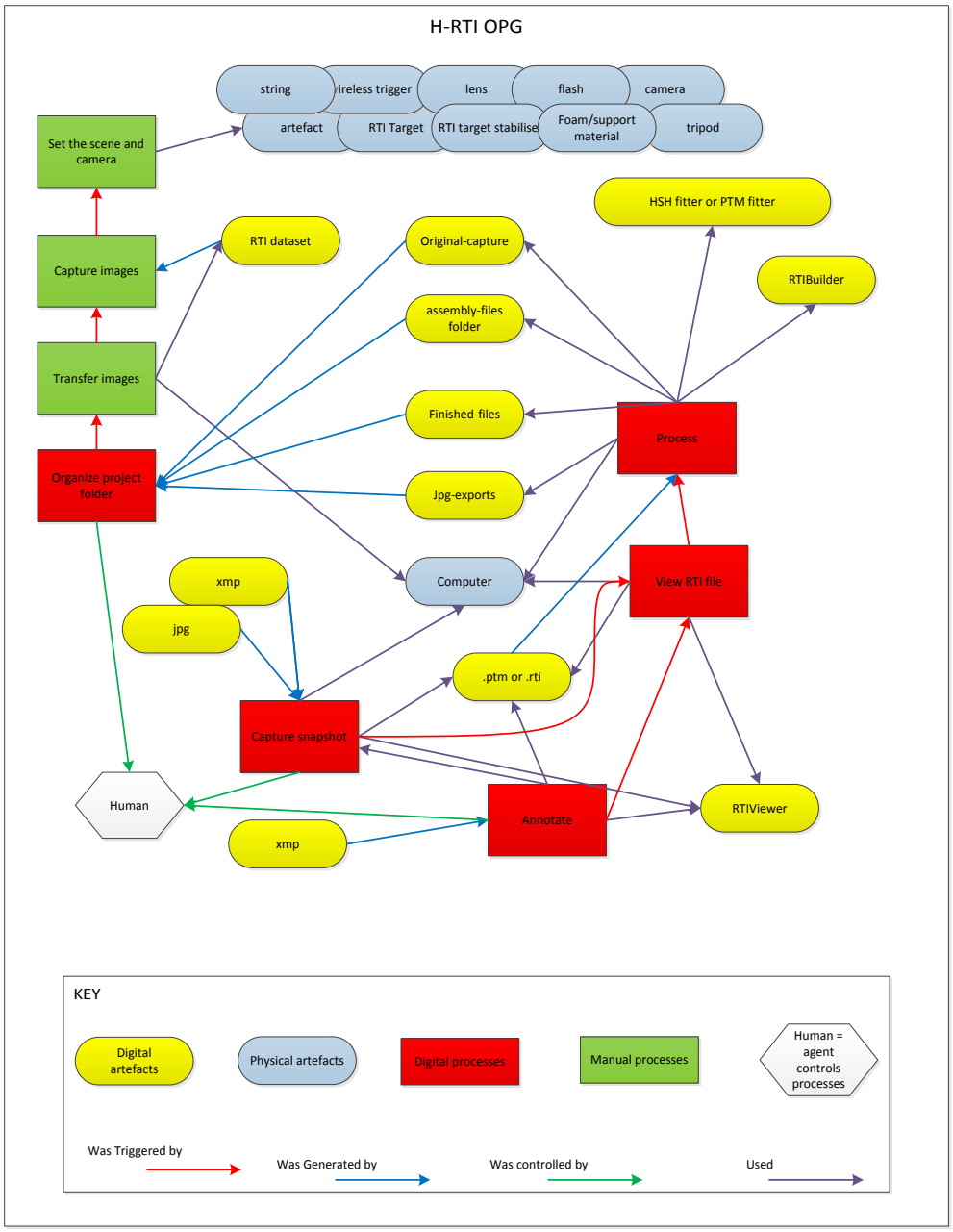
5.3.1 Methodology

5.3.1.1 Data capture

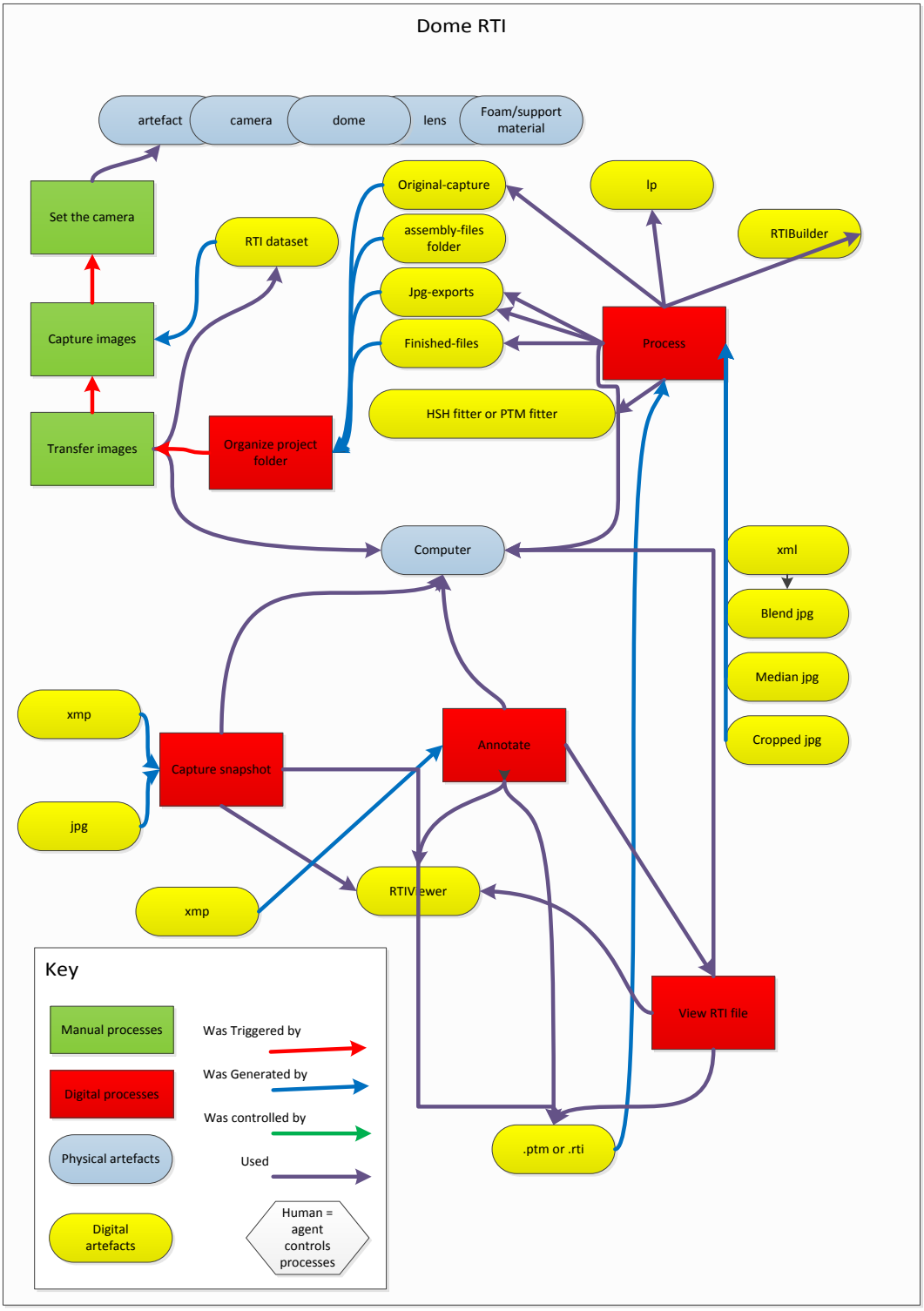
The methodologies used for reflectance data capture were the Highlight RTI and the dome method. In addition to normal H-RTI and dome RTI, an auxiliary mechanical arm and the microscopic H-RTI, as well as a mini dome suitable for macroscopic and microscopic RTI were tested. Open Provenance graphs were

used to represent graphically the processes that take place, the physical and the digital components that are either used or generated (Graphs 23-24).

One of the most significant components encouraging the development and adoption of RTI has been the flexibility of its methodology. Different imaging set-ups, such as transmitted imaging, infrared and ultraviolet imaging as well as optical microscopy can be implemented, presenting new possibilities for research, which are also able to benefit from a broad related literature on image processing, computer vision and graphics. The integrated RTI methodologies proposed will be presented in the following sections.



Graph 23: Open Provenence Graph for H-RTI. Digital (yellow ovals) and physical things (blue ovals) that take part in the series of processes, either physical (green rectangles) or digital ones (red rectangles), as well as the relationships that are formed between them are represented (Graph author's own).



Graph 24: Open Provenence Graph for Dome RTI (Graph author's own).

5.3.1.1.1 Microscopic RTI

Microscopic RTI can be captured either with the Highlight RTI method or with a mini-dome method. Initially, the microscopic Highlight RTI method was tested. The equipment used included a microscope equipped with a camera, a pen light, straight sewing pins with ball-shaped, glossy, plastic heads and sharp point, plastazote foam sheet (material commonly used in museums for storage of fragile items) and modelling clay or plasteline. The laboratory set-up for microscopic H-RTI is depicted in Figures 121-122.

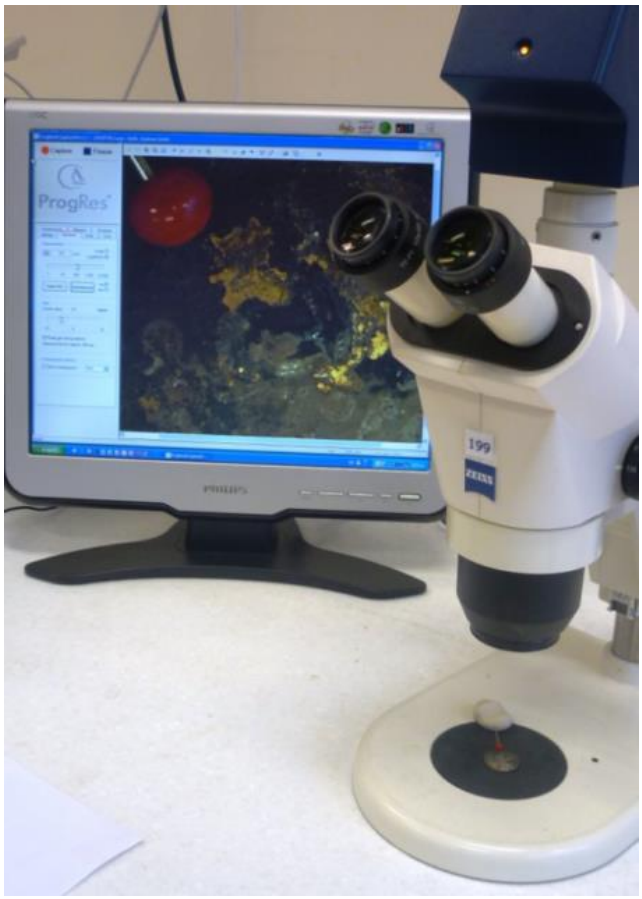


Figure 121: Microscopic H-RTI laboratory data capture set-up. The object is placed under a microscope equipped with a camera and a monitor. The positioning of the tiny glossy ball is possible using plasteline or modelling clay. Archaeological Museum of Thesssaloniki (Image author's own).

Figure 122: Microscopic H-RTI laboratory data capture set-up. The object is placed under a microscope equipped with a camera. The positioning of the tiny glossy ball is possible by sticking a pin with tiny glossy ball into a sheet of polyethylene (plastazote) foam sheet. By manually moving a pen light around the object microscopic images illuminated from different lighting positions can be captured. Archaeological Museum of Amphipolis (Image author's own).

The application of highlight image capture technique under magnification is much more demanding than normal H-RTI. Setting up the scene for microscopic RTI capture requires the best use of the available space. The glossy plastic-headed pins were used as highlight targets because of their variety of head sizes (1–4mm diameter) and lengths (20–50mm), the low price and the easy positioning with plasteline or modelling clay, or by sticking the pin into a sheet of polyethylene (plastazote) foam sheet. A polyethylene sheet is recommended because it also provides the necessary support for the object being examined. Another problem is that the microscope arms block some of the light from specific directions (almost 25% of the lighting positions). Alternative types of microscope should be considered. The millimetre-level accuracy in light-to-subject distance required for microscopic RTI is extremely difficult to achieve, considering that the light-to-subject distance should be 4× the diameter of the subject. A rotation ring or a mini dome would speed data acquisition and increase the quality of captured data.

Micro-dome lighting would better address the problems listed above, so it is recommended. Based on the above observation, an experimental microscopic RTI dome was built. The first one was a simple wooden structure, equipped with 18 LED light positioned in 3 different angles (Figure 123). Following promising results, a more complex metal dome, suitable for microscopic data capture, was designed and built (Figure 124). The second dome is capable of capturing 64 microscopic images, four images from different angles to the object's plane, from each of the 16 positions of the periphery of the dome. The dome can be turned 90 degrees, in order to place the artefact securely on a stable plate. A metallic ring, joined with the dome, is located over the artefact plate. The metallic dome, equipped with four LED lights, is moving clockwise around the artefact's plate. It is impossible for the moving dome and the ring to be separated or to touch the artefact (Figures125-127). Apart from microscopic RTI, the same dome can also be used for macroscopic RTI data capture, for example for coins or small fragments. The process of microscopic RTI data capture is represented in Graph 25.

Figure 123: The first experimental wooden mini-dome in use in the Archaeological Museum of Thessaloniki (Image author's own).

Figure 124: The mini-dome in use in the Archaeological Museum of Thessaloniki (Image author's own).

Figure 125: Digital images and graphical representation of the mini-dome (Image author's own).

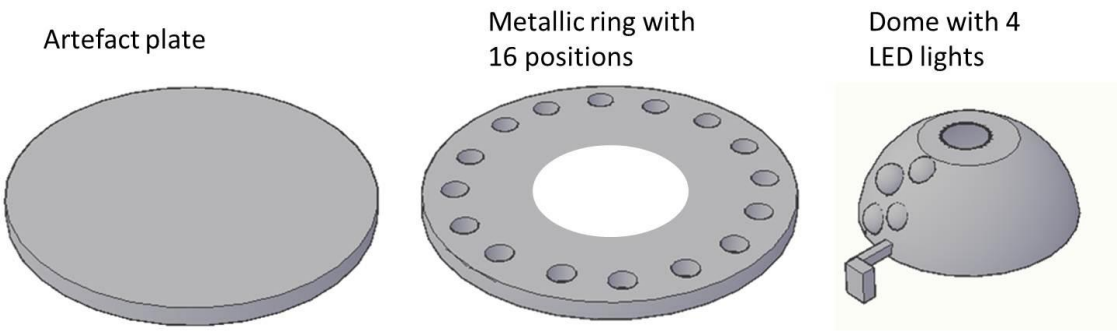


Figure 126: The mini-dome's assembly (Image author's own).

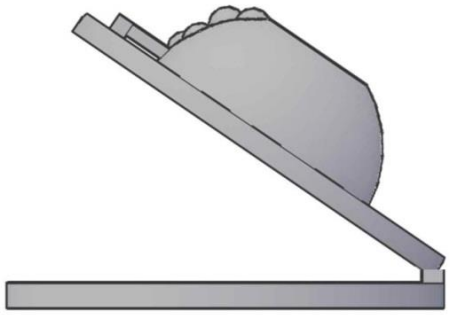
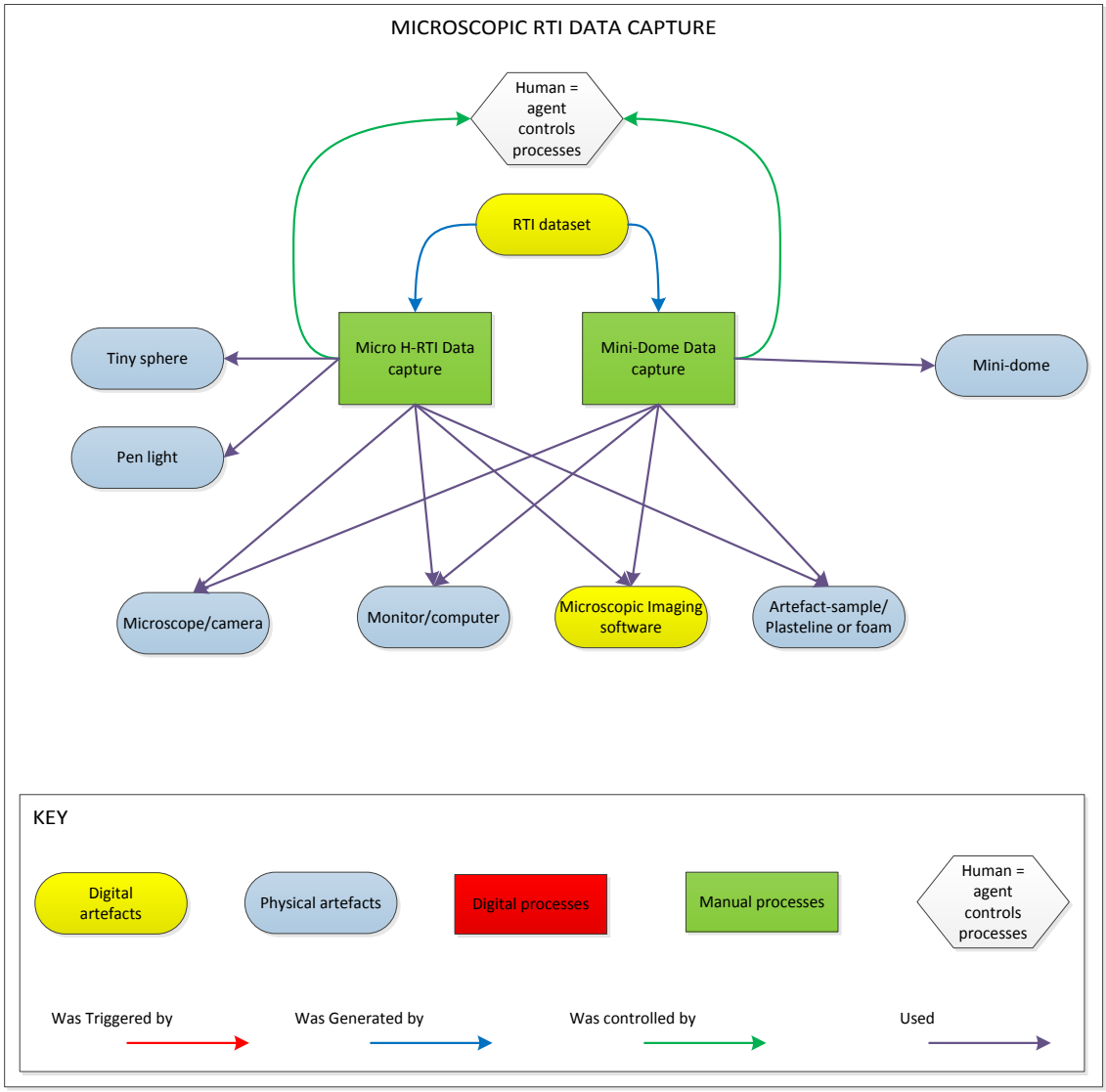


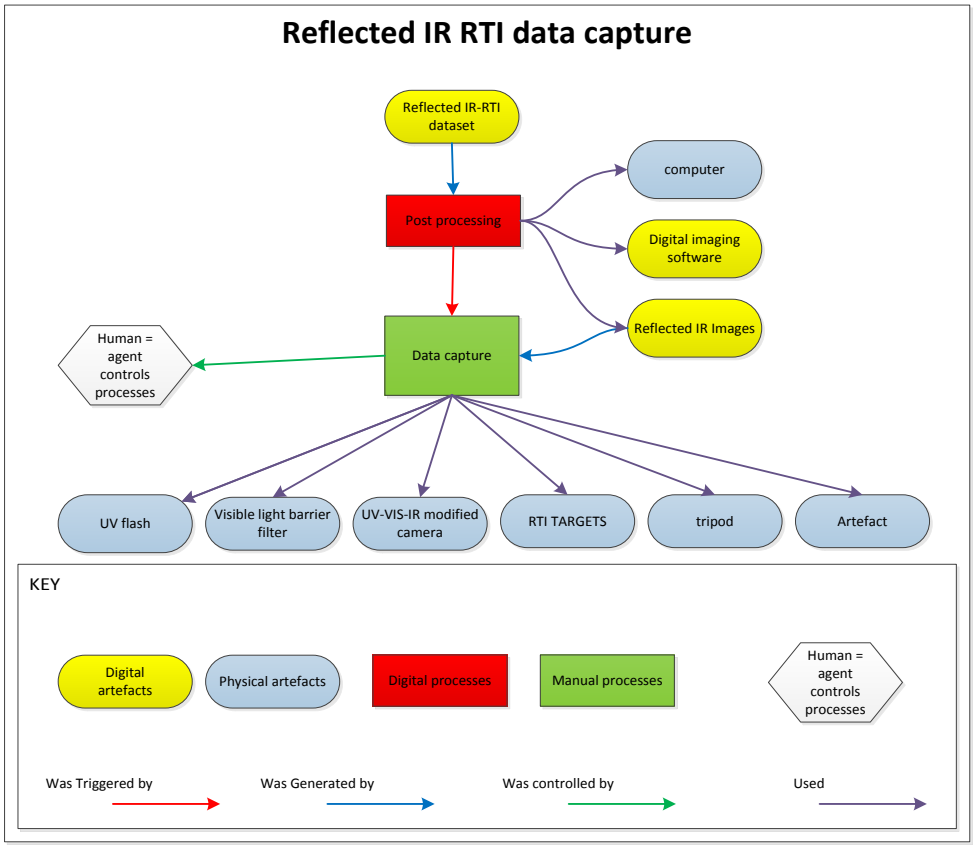
Figure 127: The dome can be turned up to 90 degrees (Image author's own).



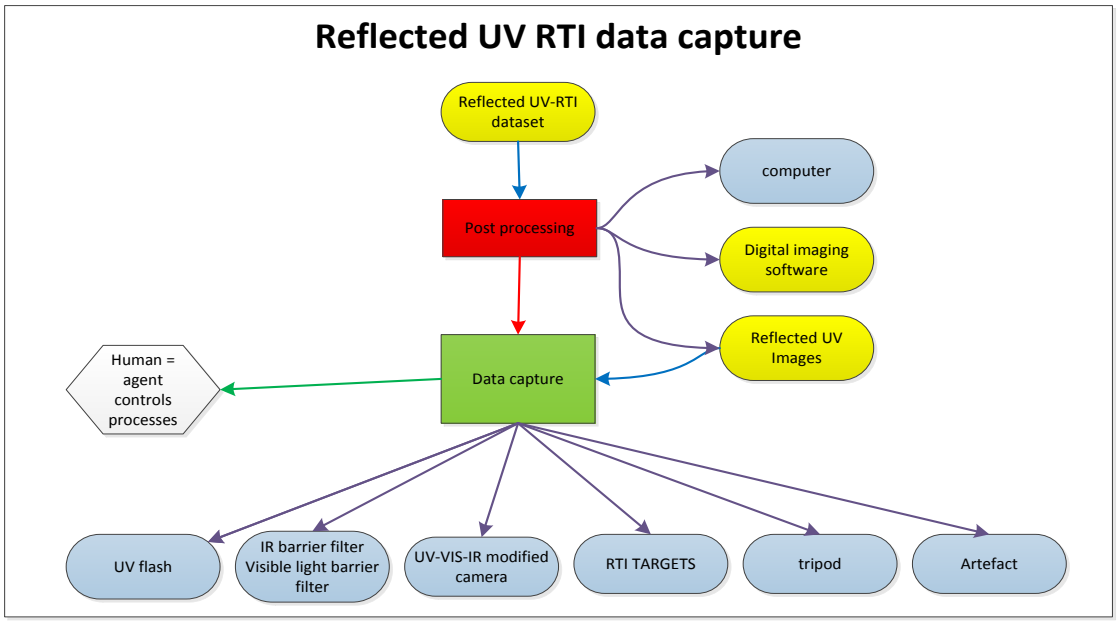
Graph 25: Open Provenance Graph for microscopic RTI data capture (Graph author's own).

5.3.1.1.2 Multispectral RTI

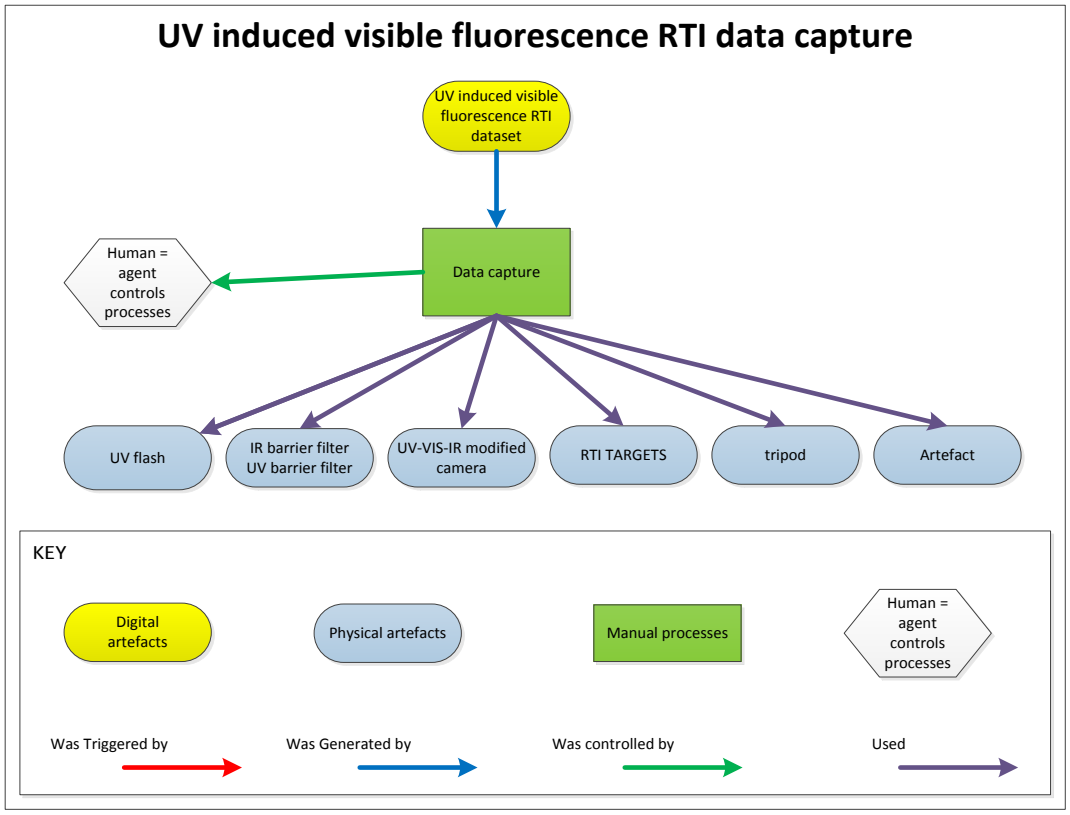
A complete multispectral RTI visualization includes additional captures in the infrared and ultraviolet spectral region. The Highlight RTI multispectral datasets were captured with a UV-VIS-IR modified DSLR camera, a range of filters and IR or UV radiation sources. These methodologies were tested in the conservation laboratory of the Archaeological Museum of Thessaloniki and the Archaeological Imaging laboratory of the University of Southampton. The IR-RTI data set is comprised of a series of infrared images captured with a range of filters (720nm, 760nm, 850nm, 950nm). The reflected ultraviolet RTI datasets were captured with a UV transmitter filter (HOYA 330) and an IR barrier (SCHOTT BG 38). The ultraviolet induced visible fluorescence RTI datasets were captured with an IR and an UV barrier (B+W 021) filter. The subjects were irradiated by IR light emitting diodes (LED) or a UV flash from different angles. The processes of multispectral RTI data capture are represented in Graphs 26-28.



Graph 26: Open Provenance Graph for IR-RTI data capture (Graph author's own).



Graph 27: Open Provenance Graph for reflected UV RTI data capture (below) (Graph author's own).



Graph 28: Open Provenance Graph for UV induced visible fluorescence RTI data capture (below) (Graph author's own).

An arm for advanced data capture of medium size objects, proved to be helpful. A cylindrical base provides a secure foundation for a vertical axis. The arm can follow a vertical and clockwise movement, assisting data capture in that way. The radiation source can be securely placed on the arm's additional extension so as to be positioned in different points of the arm, having various orientations (Figure 128).

Figure 128: The RTI arm in use in the Archaeological Museum of Thessaloniki (Image author's own).

5.3.1.1.3 Transmitted RTI

The transmitted RTI methodology is inspired by transmitted photography, a setup proposed for conservation documentation of translucent materials, canvas paintings, mounded papyri, photographic material, and works of art on paper or archival material. The transmitted RTI is created from a series of images captured with transmitted illumination and/or radiation and a lighting positions file. It was tested in the visible and the infrared spectral area. Three different data capture strategies were tested: transmitted-dome-RTI, highlight transmitted RTI, and a two-camera methodology.

The transmitted-dome-RTI methodology requires the use of a modified dome (Figure 129). A normal dome positioned upside down was used for testing. The only modification was the addition of a stand so as to support the dome in an upside down position. The dome method is recommended for transmitted data capture due to the ease of use, and considerably less time being needed for data capture and processing, and moreover the quality of data captured.

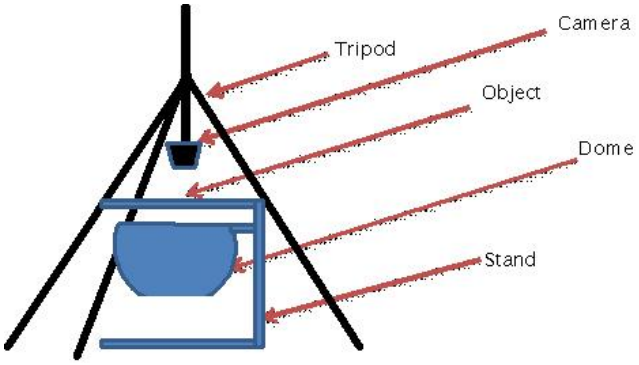


Figure 129: Graphical representation of set up for transmitted RTI capture with the dome method (Image author's own).

The capture of highlight transmitted RTI datasets requires pre-capturing of the lighting positions as well as the accurate marking of these positions, in order to be used during data capture and processing of the transmitted RTI data. This process is very time-consuming and mismarking the lighting positions is very easy. One of the techniques tested for transmitted-H-RTI employs two cameras (Figure 130). One camera is focused on one side of the object. The second one is placed on the opposite side and is focused on the shiny sphere beside the object. The latter acquires the necessary data for the construction

of the light position file, while the former captures the object under examination in transmitted illumination. The advantage of the two cameras method is that the lighting positions and the transmitted RTI dataset are captured simultaneously, minimising the possibility for mismarking the lighting positions. Nevertheless, the technique is impractical in particular for trans irradiation applications, where not only two cameras but also two different light sources are necessary. At least two people (if not three) need to be employed.

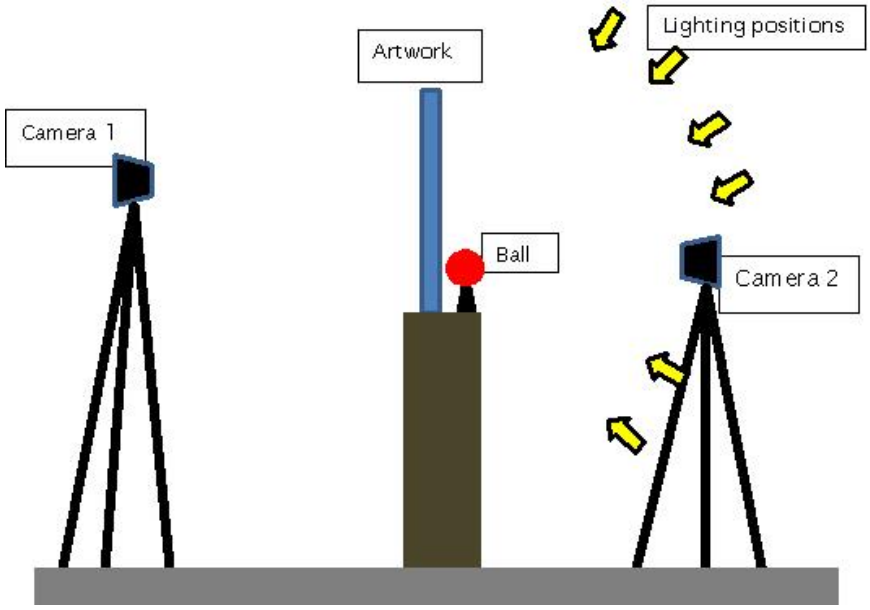
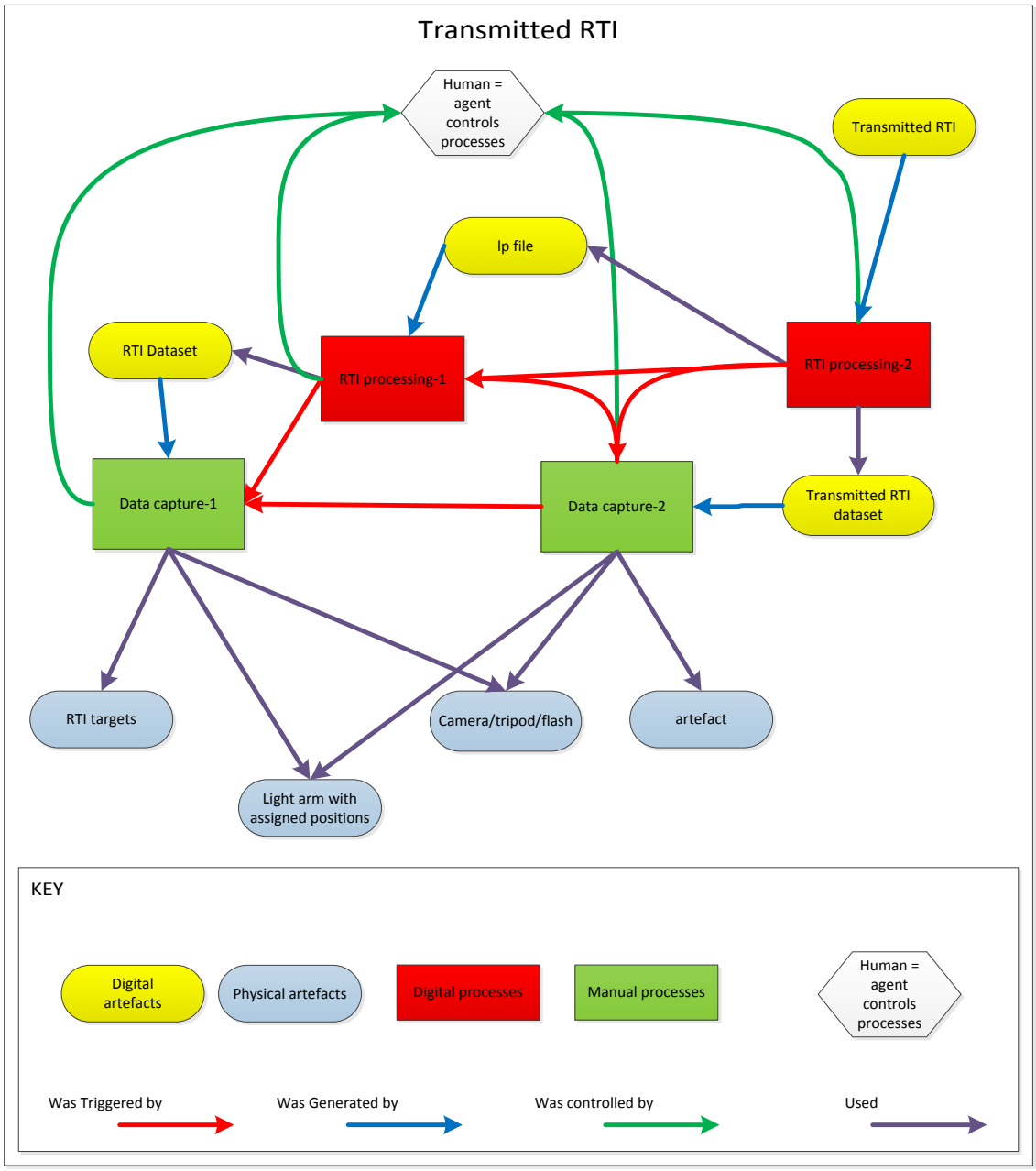


Figure 130: Set up for transmitted RTI data capture using two cameras method (Image author's own).

An alternative option is the use of a light arm in predefined lighting positions. The lighting position (lp) file can be obtained by pre-capturing a sphere from specific lighting positions, which can be re-used for capturing the RTI dataset images. In the case of artefacts where only low angle lights are employed, such as glass mounded works of arts (papyri and paintings are most commonly found in museum collections), placing the object on a Plexiglas base and moving the light around the object at the height of the object and slightly beneath enables the acquisition of a set of transmitted photographs.

The transmitted RTI data capture is represented in Graph 29.



Graph 29: Open Provenance Graph for Transmitted RTI data capture (Graph author's own).

5.3.1.2 Processing

The data processing methodology uses the RTIbuilder software. In case of Highlight RTI, images are loaded and saved, the sphere is selected and added by the user, and then the program executes sphere and highlight detection. Finally, the Polynomial Texture Map (PTM) or the Hemispherical Harmonics (HSH) fitter completes fitting and results in artefacts visualised in polynomial texture map or reflectance transformation imaging format (*.ptm or *.rti), using either the polynomial texture map, developed by HP researchers, or the hemispherical harmonics fitter, developed at the University of California, in collaboration with CHI and T. Malzbender (Graph 30). In the case of dome RTI, data capture and processing is different because each dome has a pre-build lighting position file. There is no need to add spheres to the scene in the data acquisition stage. During processing the builder uses the pre-build lighting position file and continues with fitting (Graph 31).

Processing of microscopic and multispectral RTI datasets follows the same methodology with visible RTI. In case of infrared and ultraviolet RTI, the images were processed following the common recommendations (transition to greyscale) before the RTI processing. Similarly, for FCIR-RTI the visible and IR dome RTI datasets were initially processed, following the FCIR and then the RTI methodology.

The combination of two RTI datasets into one via digital image merging just after data capture, using the dome method, and before processing proved to be useful for comparative purposes, as it enables the user to simultaneously examine two sides of the same object (Figure 131).

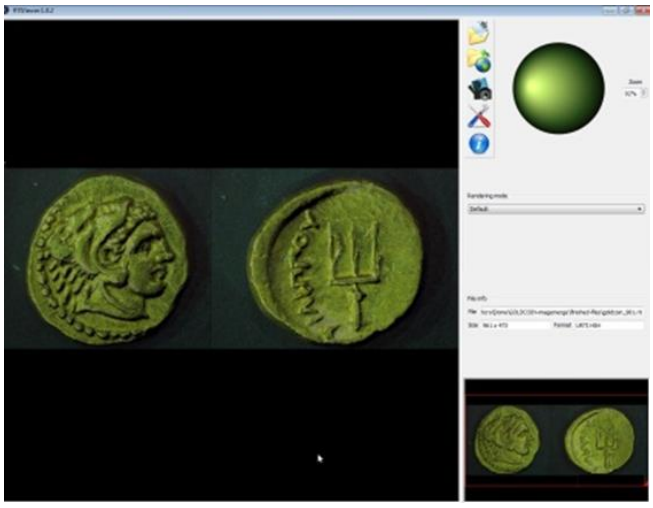
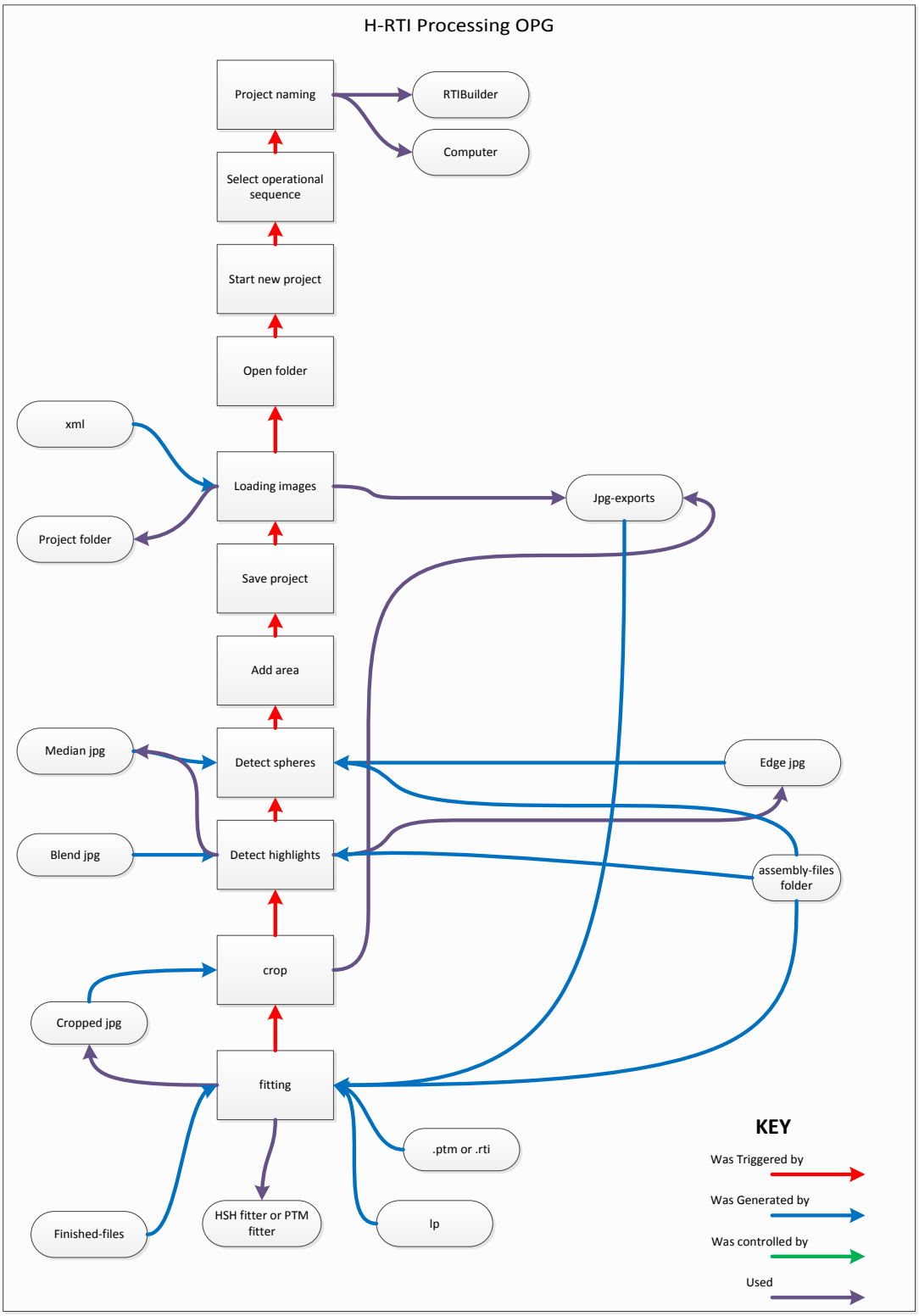
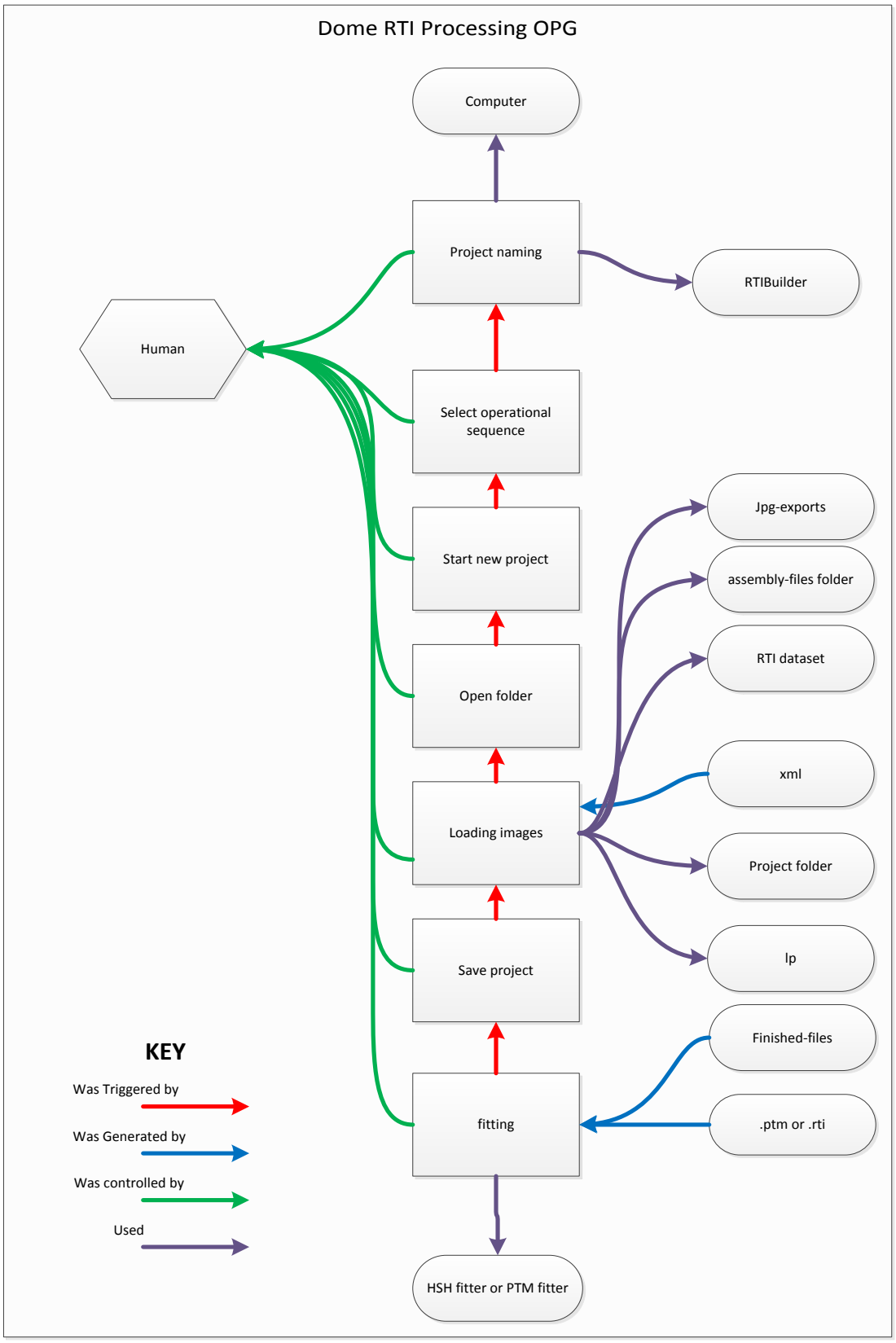


Figure 131: Snapshots of the RTI viewer - screen view after merging images of two different datasets captured using the

dome method, before processing (Image author's own).



Graph 30: Open Provenance Graph of the H-RTI processing pipeline (Graph author's own).



Graph 31: Open Provenance Graph of the Dome RTI processing pipeline (Graph author's own).

5.3.1.3 Viewing and Annotations

PTM and RTI files were viewed via specialized software, such as the RTI viewer (ISTI-CNR/CHI RTIViewer) and the PTM viewer (HP Labs PTM Viewer). The files were annotated using the annotation utility in the latest release of the RTI viewer software (Figure 132) (see section 3.2.1.3 for a discussion on viewing .rti and .ptm files).

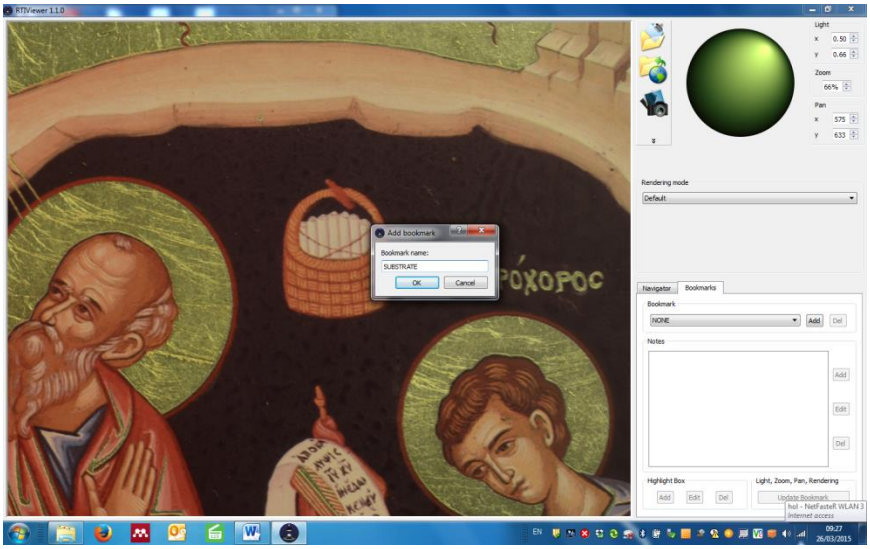


Figure 132: Using the Annotation Utility, RTI Viewer (Image author's own).

5.3.2 Results and discussion

5.3.2.1 Paintings

5.3.2.1.1 Painted panels

RTI visualization of icons emphasises surface anomalies of low relief details. Characteristic features, such as brush strokes, can be detected and areas with discontinuities can be easily documented (Figure 133). Thorough RTI examination of the surface topography reveals signs, which provide an insight into manufacture, such as gold gilding technique (Figure 134). Hence, RTI can be extremely useful for diagnostic examination, investigation of painting techniques and condition reporting.[21]

[21] See Digital Library, folder section5.3, files REP_PWOO_I1_BW-VIS_MA-H.rti and REP_PWOO_I2_VIS-MA-H.ptm

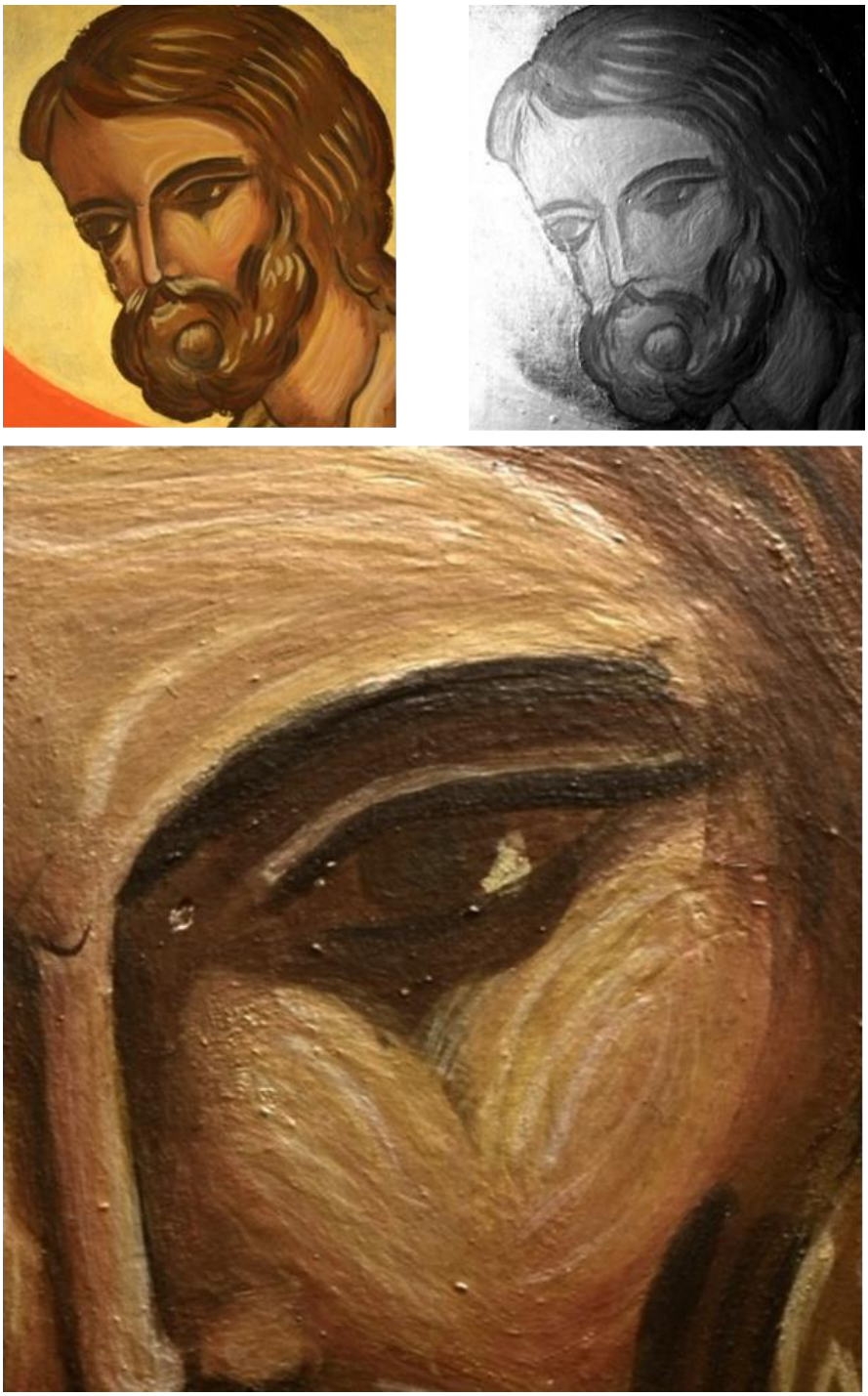


Figure 133: Icon, replica, digital image (top left) and RTI visualizations. RTI highlights the texture of the painting, emphasizing the brush strokes, emphasizing the brush strokes (Image author's own).

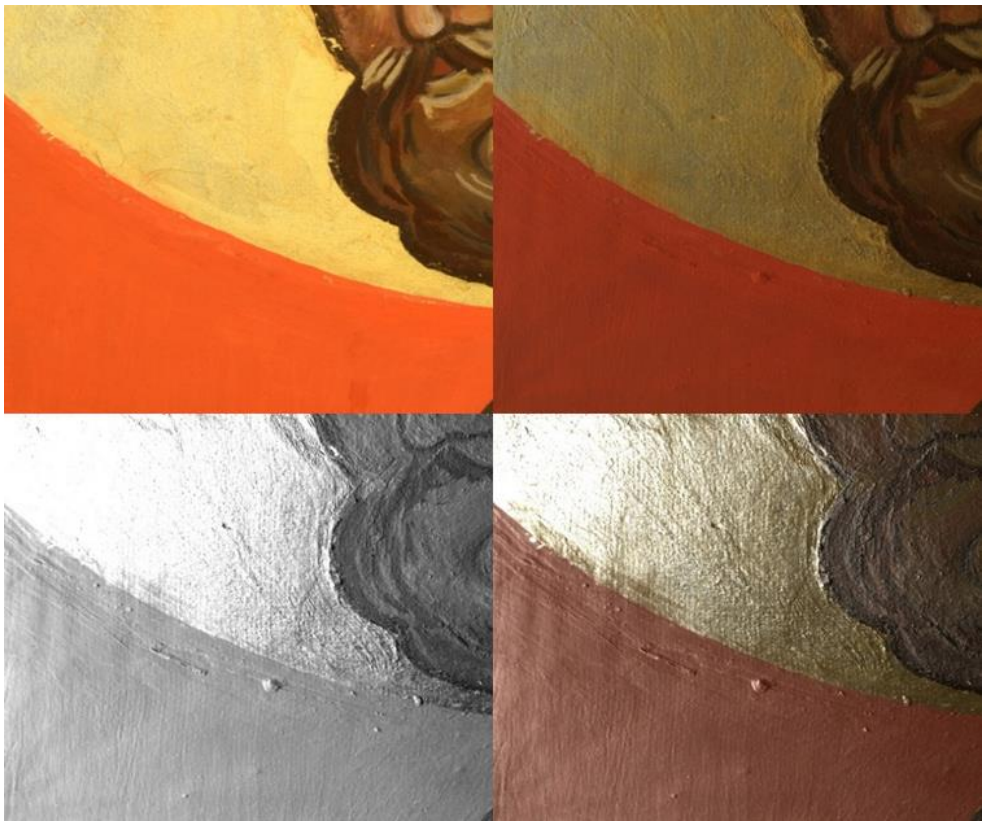


Figure 134: Icon, replica, detail of gold gilded area. Clockwise from top left, digital image, and RTI visualization in default, and specular enhancement rendering mode (Image author's own).

The icons' IR examination reveals the preparation sketch and presents an insight into pigments and colour layers. Details of the final brushing disappear, providing an enhanced view of the preparatory drawing (Figure 135). The pigments used present a variety in transparency in IR radiation, from the opaque black background to the transparent clothing of St John. In the visible monochrome image, there is no clear differentiation between the grey tone of the red, the sienna and the blue colours. On the contrary there is an observable difference in the response of the red and the sienna and blue colour on the infrared image (Figure 136).

Figure 135: The icons, digital images desaturated (left) and IR images (right) (Image author's own).

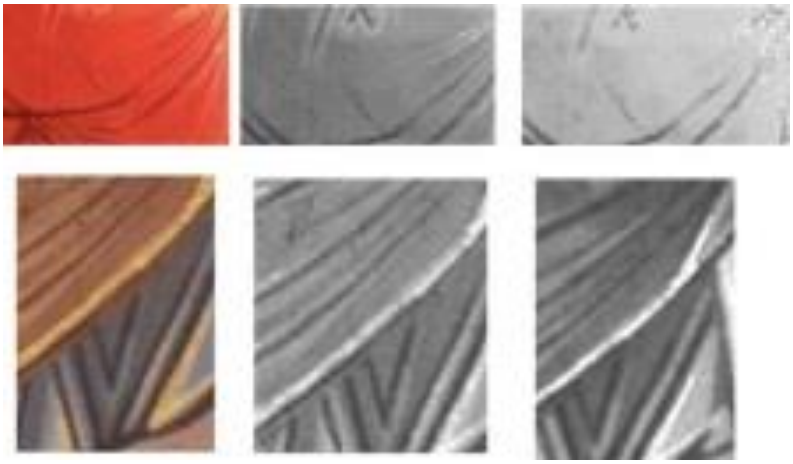


Figure 136: Details of red, blue and sienna colour in digital image (left), desaturated (middle) and IR image (right) (Image author's own).

The IR-RTI of the icon, taking into consideration their planar shape and their reduced three-dimensional characteristics, gave interesting results, revealing hidden features and the preparatory drawing. IR-RTI by penetrating the varnish layer, the texture of the substrate can be observed. RTI reveals the texture of the varnish applied, while in the IR-RTI renderings the texture of the substrate is visible, along with its deformations, such as the vertical crack on the area of the basket (Figures 137-138). Areas where the colours have not been applied uniformly due to surface variation of the substrate become obvious, as well as crack in the application of the gold leaf (Figure 139). The preparatory lines, along with their texture, can be examined. Final brushing of details disappears, emphasizing the three dimensional properties of the preparatory drawing (Figure 140). The best means of comparison between normal and IR RTI is the normal maps in the visible and infrared spectral areas (Figure 141)[22].

Figure 137: Icon, detail, RTI (left) and IR-RTI visualization (right) emphasizing the vertical crack (Image author's own).

[22] See Digital Library, folder section5.3, files REP_PWOO_I1_IR-850-MA-H.rti and REP_PWOO_I2_IR-760-MA-H.rti. For comparisons with the visible RTI visualization, see files REP_PWOO_I1_BW-VIS_MA-H.rti and REP_PWOO_I2_VIS-MA-H.ptm

Figure 138: Icon, detail, RTI (left) and IR-RTI visualizations (right) emphasizing the texture of the substrate (Image author's own).

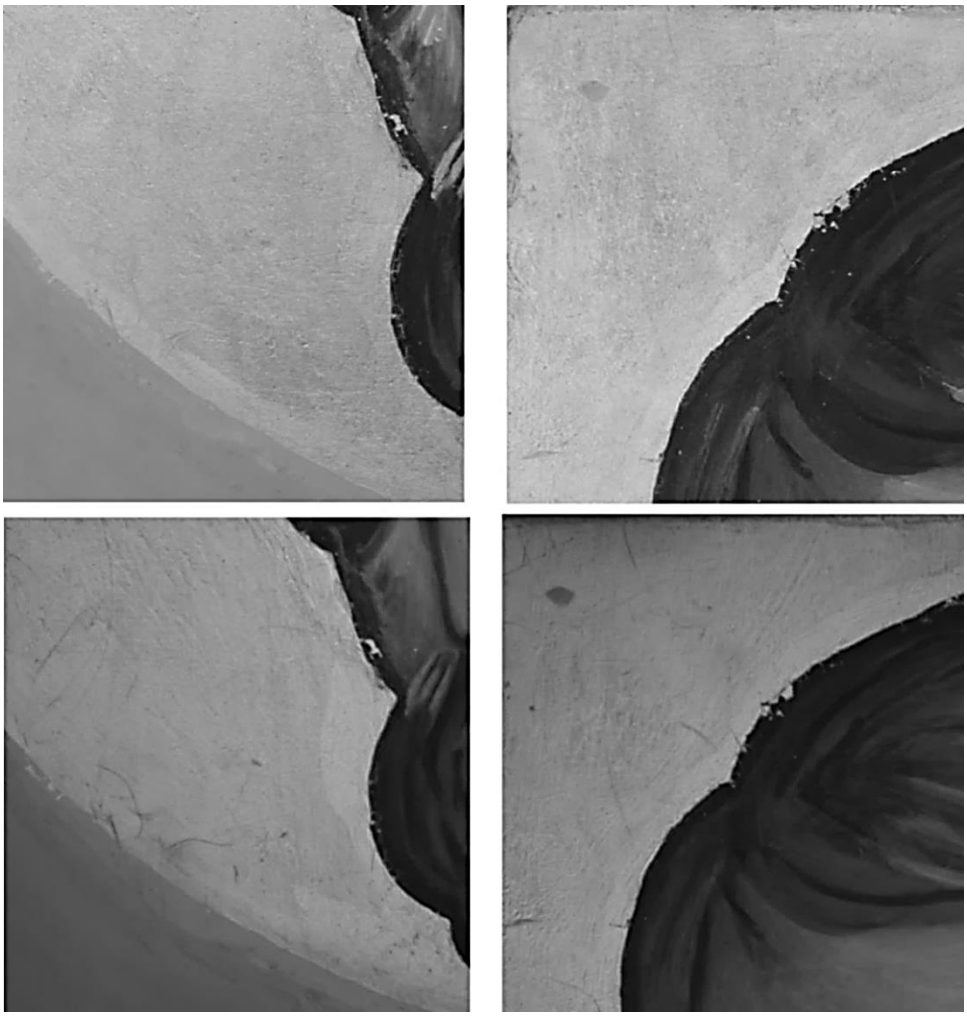


Figure 139: Icon, details, RTI (top) and IR-RTI visualizations (below) emphasizing cracks in the application of the gold leaf (Image author's own).

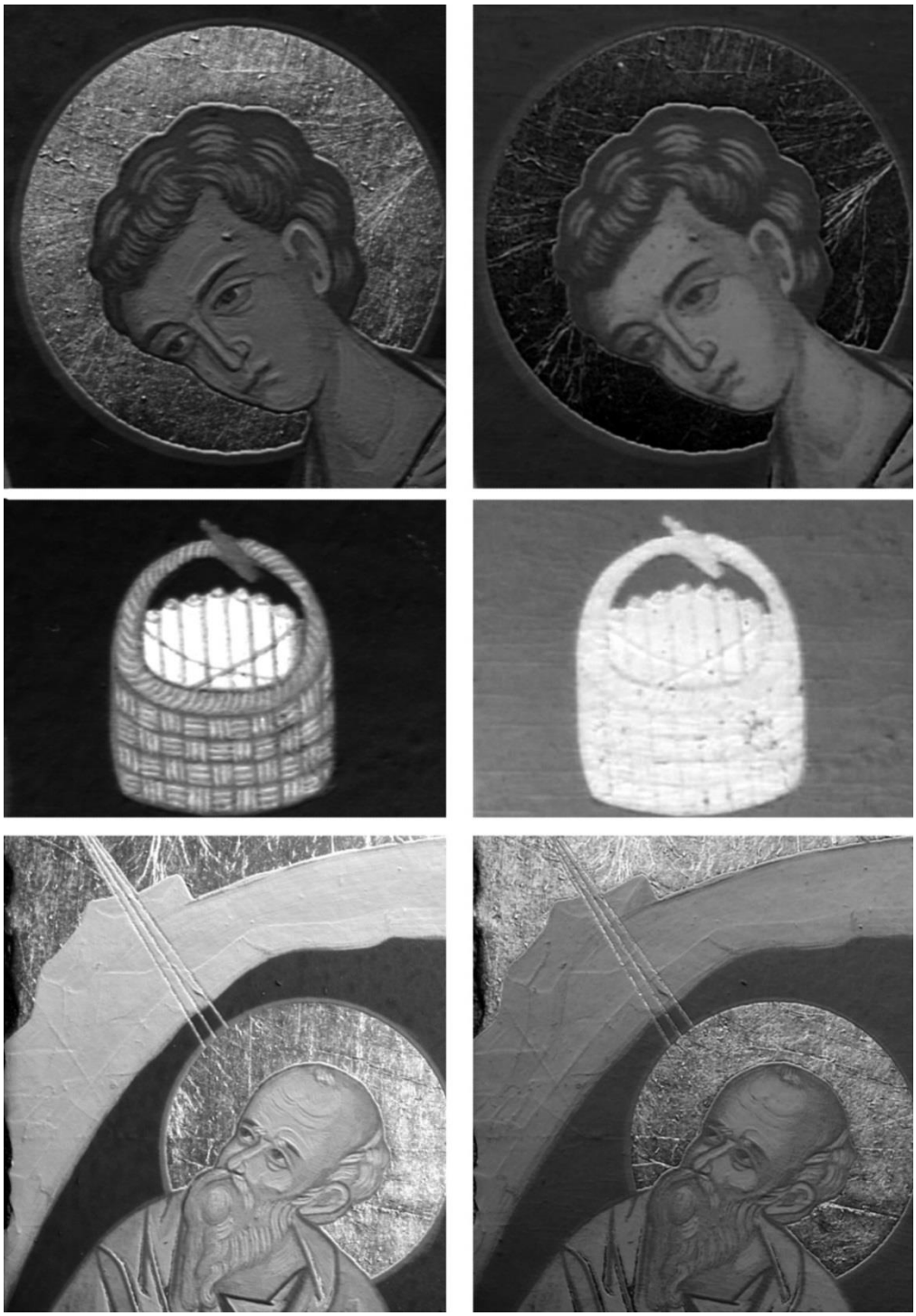


Figure 140: Icon, details, RTI (left) and IR-RTI visualizations (right) (Image author's own).

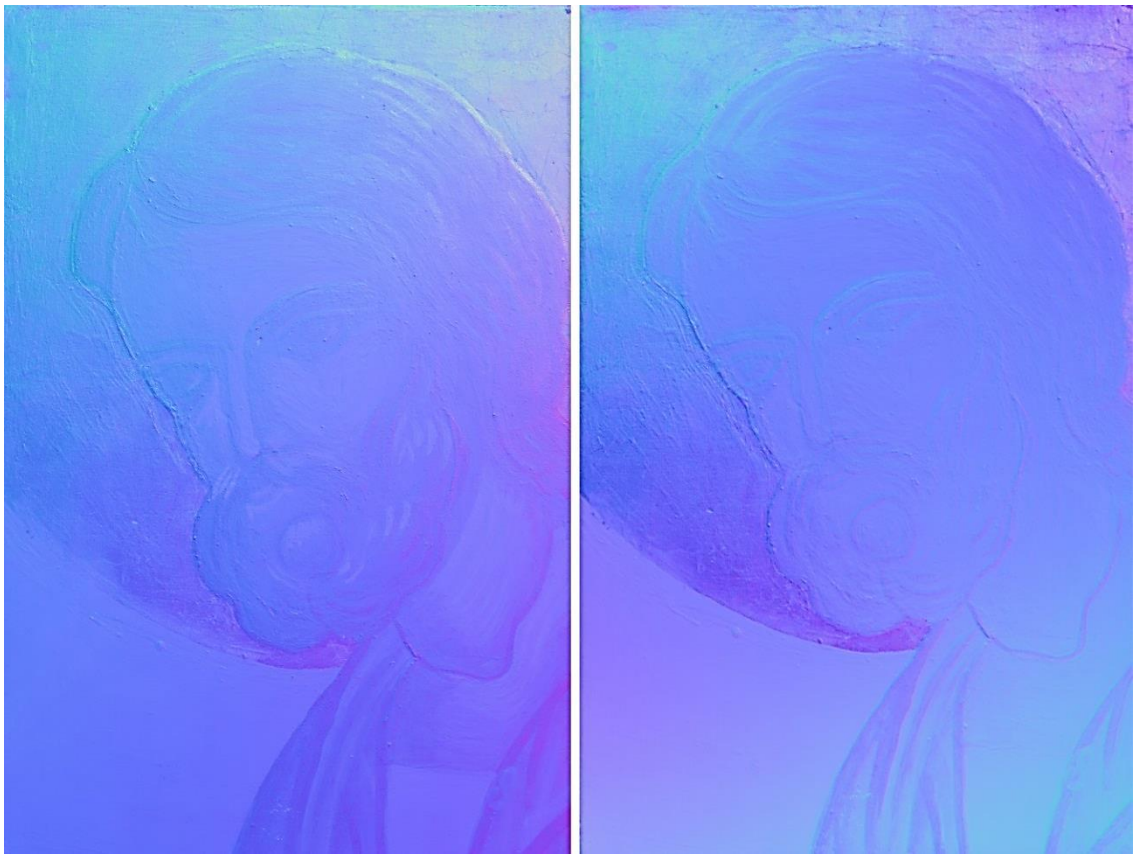


Figure 141: Icon, comparison of normal maps in the visible (left) and infrared spectral area (right) (Image author's own).

This case study serves to show the potential of RTI in the study of painted panels. Apart from the interesting conclusions regarding methodological issues, the difference between authentic material and replicas should be noted. Alterations and damage present in the authentic artworks results in an advanced level of complexity in the study of icons. Yellowed varnishes, depositions, losses and cracks have a tremendous effect in the appearance of the artwork. It is expected that the application of the proposed methods in the study of original artworks would maximise the information obtained.

5.3.2.1.1.1 False colour IR-RTI

A selection of historic pigments' testers was imaged in order to check their response in infrared radiation. The different interaction between colours and infrared radiation leads to different levels of transparency in the infrared image. Pigments that transmit IR appear transparent under IR radiation. On the contrary pigments that absorb IR radiation appear totally opaque. Other

pigments present a medium transparency, as they transmit part of the infrared radiation. Apart from the chemical composition of the pigments, other factors that affect the penetration ability of IR are the thickness of the colour layer and the material used as a binder, such as egg, water, oil, gum etc.

Visible, infrared and FCIR images of historical pigments, constructed using the traditional egg-tempera technique, demonstrate the different levels of transparency in IR radiation and the variety of pseudo-colours produced from FCIR. The latter reaffirms the results of previous FCIR studies in pigment identification. The blue and green colours appear reddish or grey in case of azurite. Yellow colours in FCIR are derived from red-orange pigments. Among them, vermillion produces the brighter, most impressive yellow tones. Dark yellow brownish colours result in pale green, while lemon yellow turn to white. Umber and raw sienna remains brown, even if it acquires a brighter tone. A possible explanation for the differentiations is the variation in granularity, which can appear as different colour in FCIR or/and the mixture of different pigment for the creation of the wanted colour hue and the material used as binder. Figures 142-143 present comparisons of visible and FCIR images of icons and colour testers.

A replica from a wall painting decoration scene of the Tomb of Menna in Egypt was the trial artefact for the first experimental FCIR-RTI. The reflected infrared image provides information about the layering of the painted artefact and reveals details hidden beneath colour. The IR radiation penetrates thin outer colour layers and reveals a number of lines, originally parts of the preparatory sketch. The FCIR image provides an insight into the composition of the pigments used (Figures 144).

The comparison of the normal visualizations leads to the conclusion that the FCIR RTI and visible RTI files reveals the same texture morphology. Their difference lies in the colours. FCIR-RTI can encapsulate in the same file data related to the texture and an initial indication about the chemical composition of the pigments. This development can assist in artefacts' examination. The simultaneous examination of surface topography in addition to the colour variations enhances the examination of painted surfaces and provides an improved method for viewing FCIR images (Figures 145).

Figure 142: Icons, comparison of visible and FCIR images (Image author's own).

Figure 143: Colour testers of historic pigments, egg-tempera technique. Digital image (up) IR image (middle) and FCIR image (below) (Image author's own).

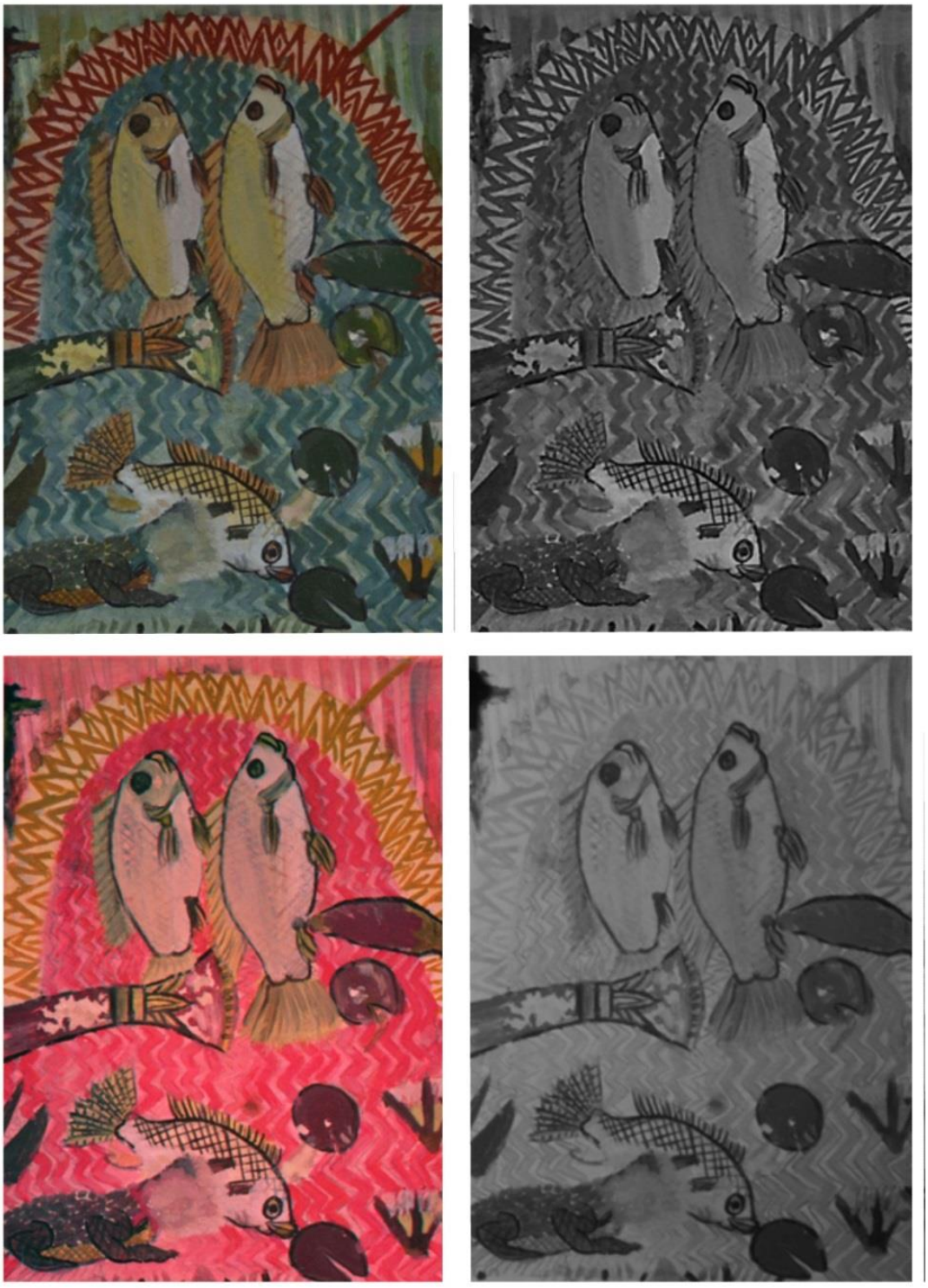


Figure 144: Painted panel, replica. Comparison of visible, desaturated, infrared and FCIR images (clockwise from top left) (Image author's own).

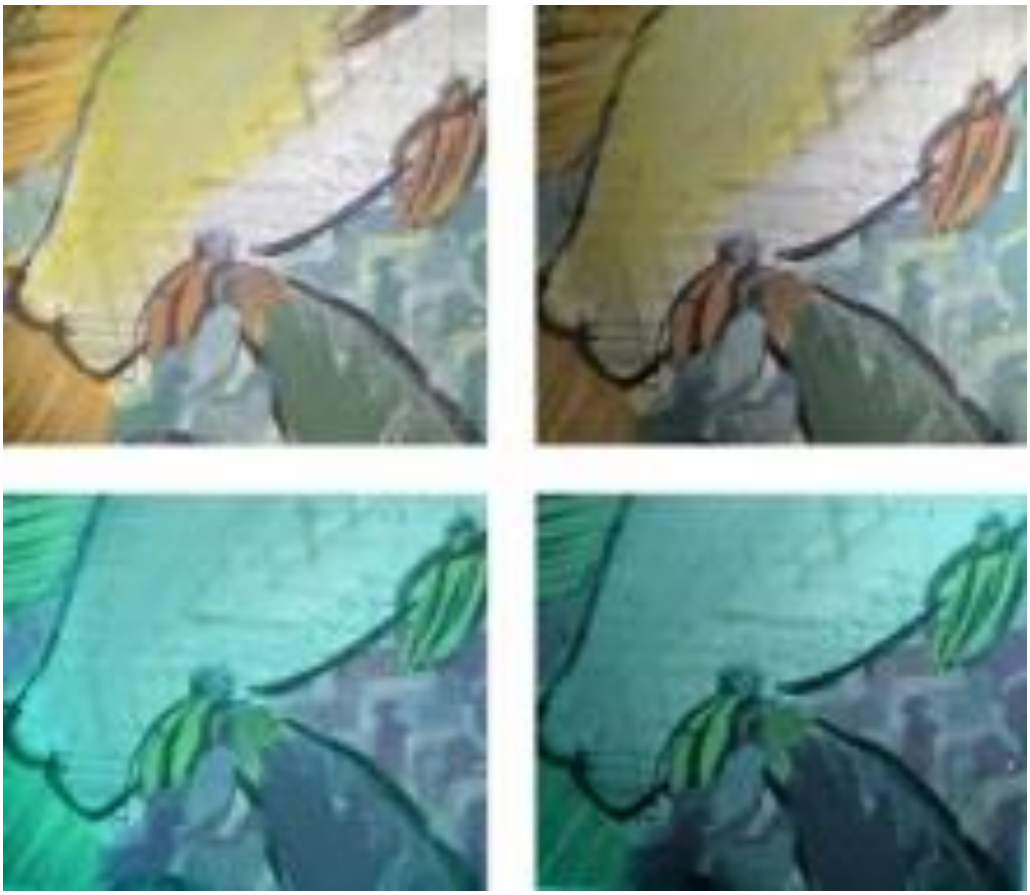


Figure 145: Detail, comparison of visible (up) and FCIR (below) images (left), visible RTI (up) and FCIR RTI (below) snapshots (right) (Image author's own).

5.3.2.1.2 Canvas Testers

The legibility of the writing depends on the properties of the overlapping layers, its thickness and the composition of the pigments used. In reflected visible images the inscription hidden beneath the colour layer or layers is hardly visible. In reflected IR images the legibility depends on the transparency of the pigments in IR radiation in addition to the surface topography. In tester 3 the readability of the inscription is clear, while in testers 2 and 1 the inscription can hardly be read. In transmitted images the readability in general is enhanced. In transmitted visible images the readability is enhanced compared to the reflected examples, while in the transmitted infrared images the results are further enhanced compared to the transmitted visible ones (Figure 146). The ambient light is crucial in transmitted imaging as shown in Figure 147.

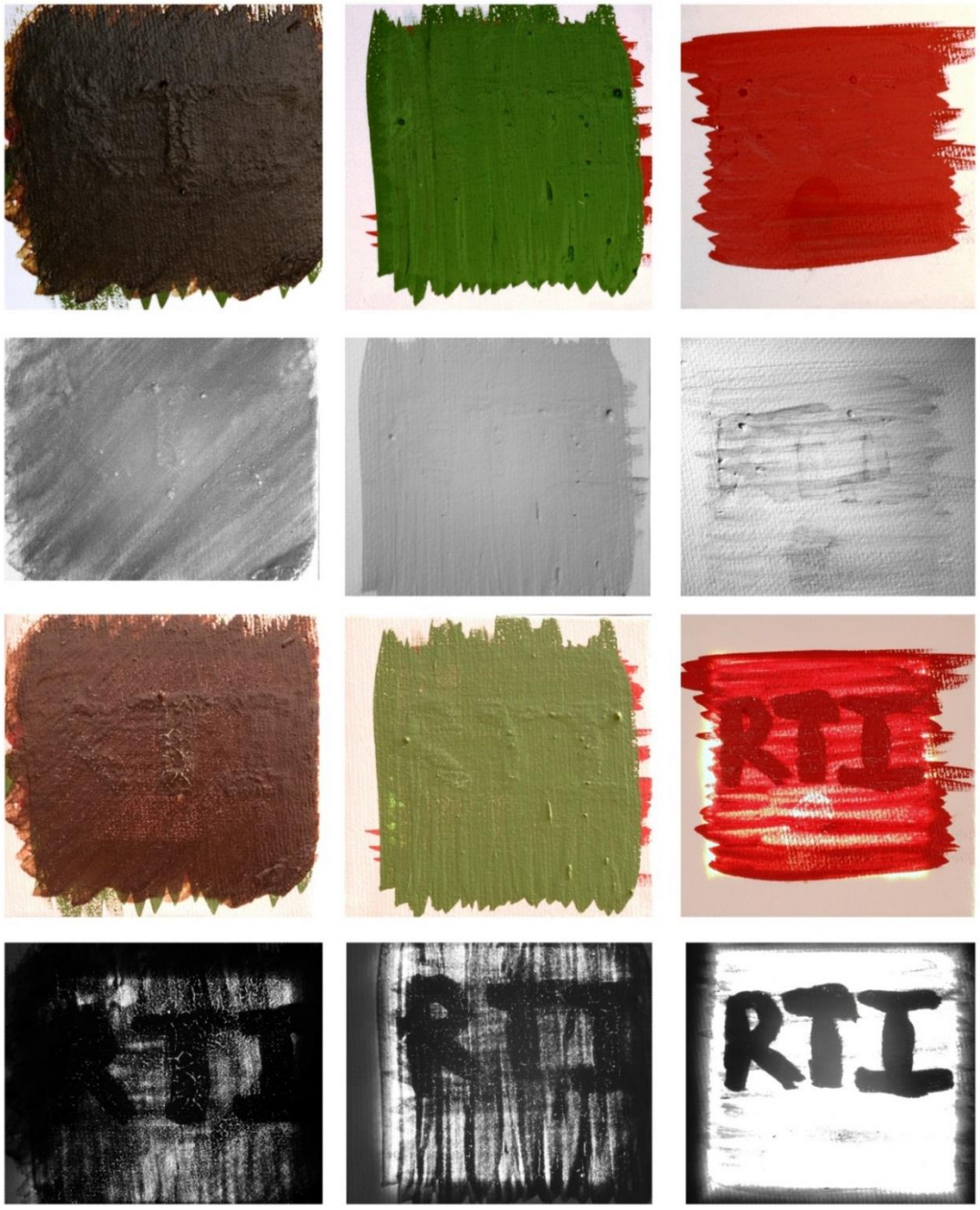


Figure 146: Canvas testers 1 (left), 2 (middle), 3 (right). Digital images, visible (top), reflected infrared (2nd row), transmitted visible (3rd row) and transmitted infrared (below) (Image author's own).

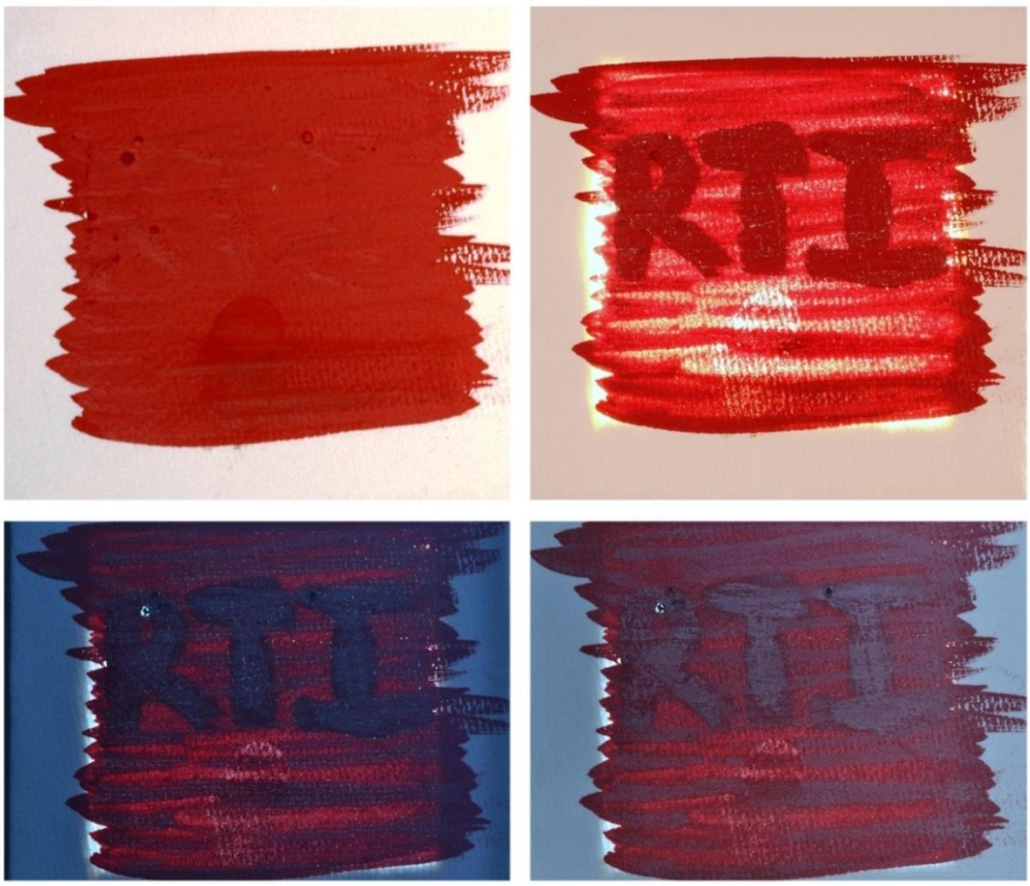


Figure 147: Tester No 3, reflected digital image, trans illumination image and RTI visualization with and without ambient light (clockwise from top left) (Image author's own).

RTI reveals the inscription by emphasizing the surface topography of the testers due to the visualization of the texture[23]. In the IR-RTI snapshots the reading is enhanced in all testers[24]. In the case of testers 3 and 2 the enhanced visualization was expected because of the known response of the pigments used. However, the superior performance of IR-RTI in tester 2 in comparison with the digital image was surprising. The most notable result is that of tester 1. Even with the presence of 3 colour layers, including one that appears opaque to IR and one of medium transparency, IR-RTI leads to satisfying results (Figure 148).

[23] See Digital Library, folder section5.3, file REP_PCAN_T123_VIS_MA_H.rti
[24] See Digital Library, folder section5.3, file REP_PCAN_T123_IR-760_MA_H.rti

Figure 148: Canvas testers 1 (left), 2 (middle), 3 (right). RTI visualizations (Image author's own).

Transmitted RTI enhances the results of transmitted imaging. The variation of colour applied on the canvas due to the painting technique, can be examined, as areas with fewer colours applied are emphasized. This enables the advanced examination of painting technique and the superior perception of the painted surface. The comparison of transmitted images and transmitted RTI visualizations suggests that the main contribution of transmitted RTI lies in its enabling of the perception of three-dimensionality which occurred in transmitted illumination and/or irradiation of artefacts. In particular tester 3, due to the limited number of colour layers applied, is an explicit example for transmitted RTI in the visible spectrum[25] (Figures 149-151).

[25] See Digital Library, folder section5.3, file REP_PCAN_T3_T-VIS_MA_MD2.ptm

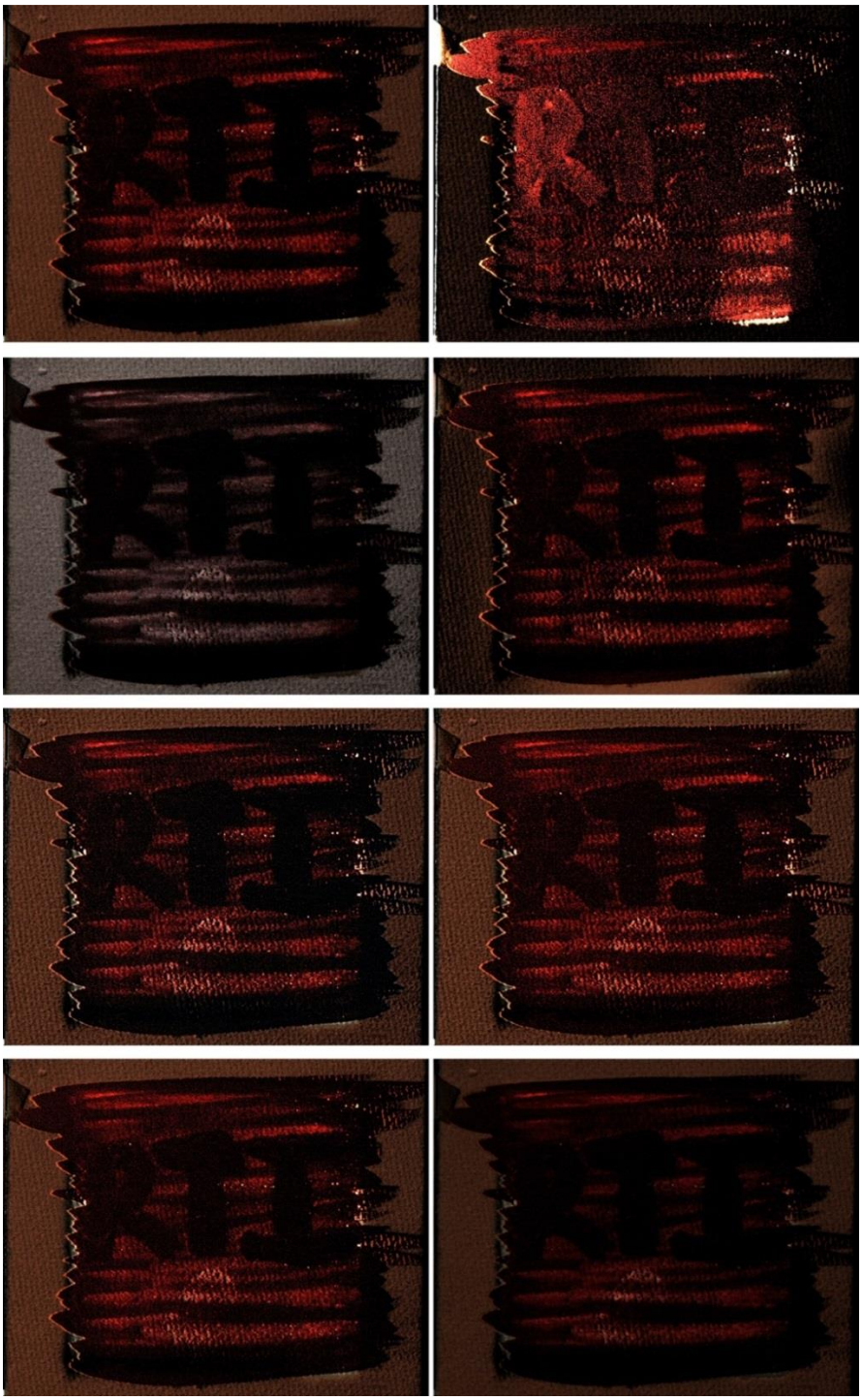


Figure 149: Tester No 3. Transmitted RTI visualizations in different rendering modes (Image author's own).

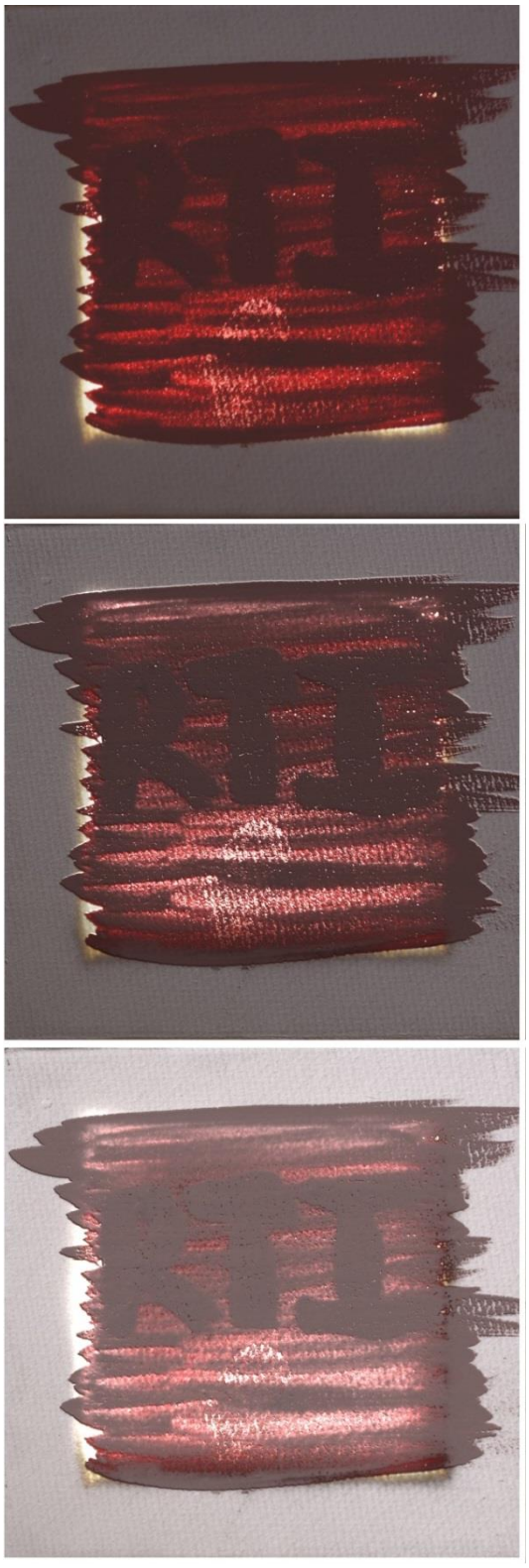


Figure 150: Tester No 3. Trans IR-RTI visualizations (Image author's own).

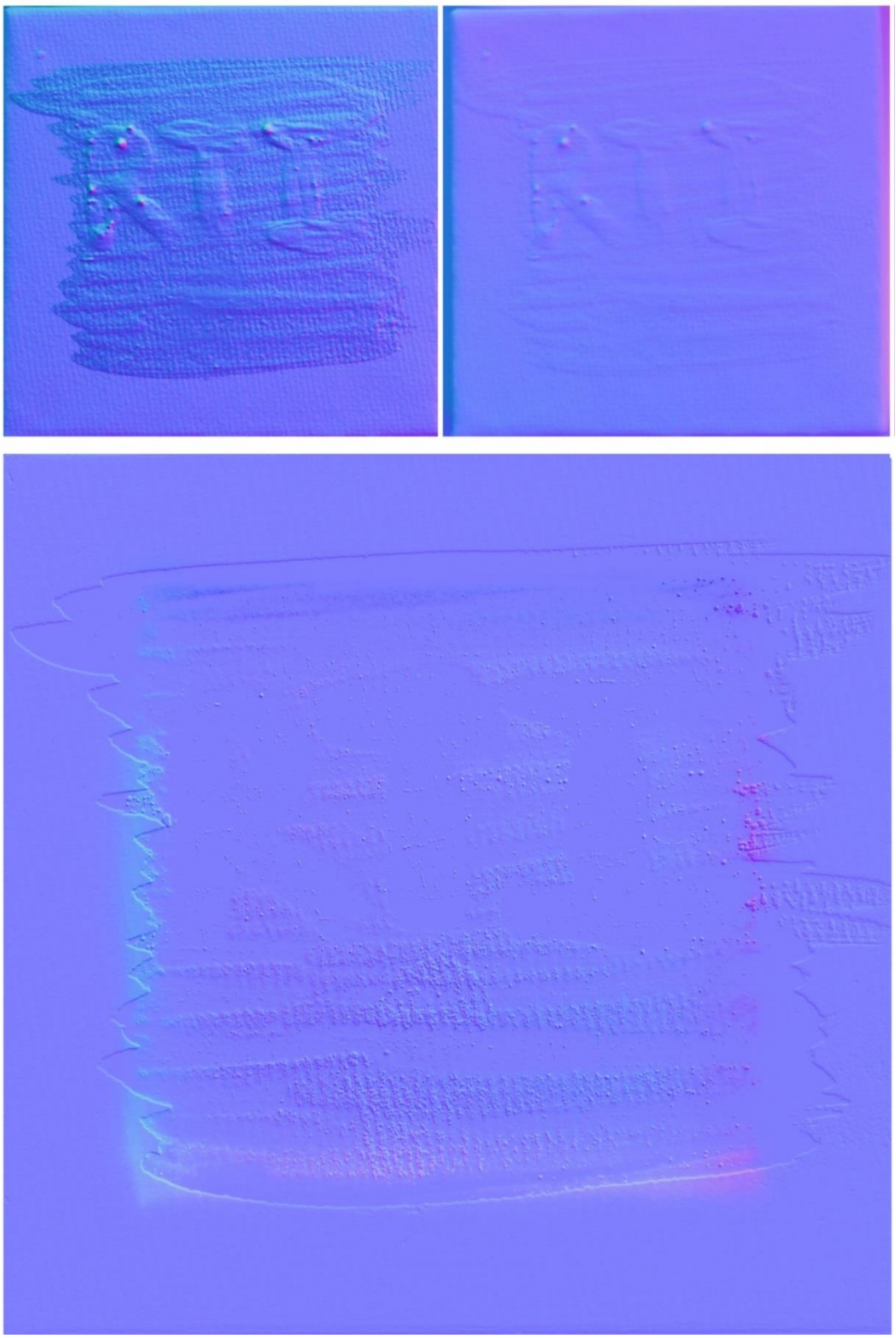


Figure 151: Tester No 3, comparison of transmitted digital image (left) and transmitted RTI visualization (right) (Image author's own).

On the contrary, transmitted irradiation in the infrared spectral area in synergy with RTI is a more appropriate methodology for surfaces with more complex stratigraphy, such as the case of the testers 1 and 2. The experimentation with canvas testers clearly demonstrates that trans illumination and irradiation can significantly improve the methodology for diagnostic examination and detection of over painting. Capturing normal RTIs of canvas paintings placed on light boxes is another modification of the basic technique that can be used as a complimentary methodology (Figures 152).

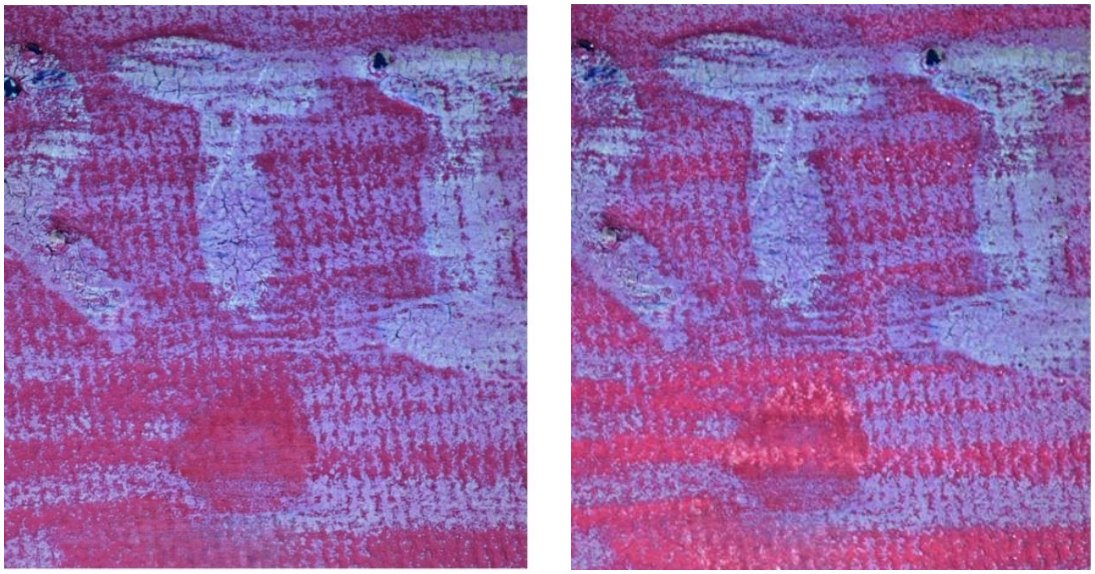


Figure 152: Tester No 3, reflected visible RTI without (left) and with (right) transmitted illumination (Image author's own).

The stroke direction is a feature that characterises stylistic techniques, and is crucial for comparisons among paintings and discrimination of painting techniques. The different imaging set-ups used in the experimentation enables a thorough examination of painting strokes. In tester 3 and 2 the strokes were detectable in all imaging set ups. However, the most useful one was the transmitted visible image for tester 3. However, for tester 2 the transmitted IR image was preferred as far as the painting style was concerned, as it highlights not only the vertical strokes of the green colour but also the horizontal strokes of the hidden red layer. In tester 1 the transmitted images present a chaotic picture in the case of strokes, while the reflected IR is the most descriptive image, which emphasize the diagonal direction of strokes clearly.

Simultaneously, capturing of the canvas testers presents the opportunity to detect the efficiency of the already presented methodologies in condition reporting and conservation documentation. The most interesting results are that of tester 1, where transmittance enables the detection of craquellere. This feature was not at all observable in reflected visible images, while only major cracks were slightly detectable in reflected IR image. The RTI visualizations significantly enhanced the results of imaging, and enabled the thorough examination of surface deformations, including the craquellere pattern.

5.3.2.1.3 Canvas paintings

In addition to the canvas testers, replica oil tempera paintings were imaged with normal RTI, IR-RTI, Transmitted RTI and Transmitted IR-RTI. Transmitted imaging (TI) techniques enable the examination of the painting history of artworks. Transmitted images record the surface under different lighting conditions, and as a result specific features of the painting technique, such as the brush strokes, the variable thickness of the painted layers across the surface, the basic lines of the drawing, which act as a preparatory drawing, are documented. Such visualizations would have been impossible using reflected imaging techniques.

TI has been applied in both surfaces of the painting. Undoubtedly the result of TI in the latter is more impressive, because in reflected light the surface of the back side does not provide any implication about the drawing (Figures 153-155). Considering the excellent state of preservation of the artworks under examination the efficiency of TI in condition reporting cannot be presented. However, neither evidences of craquelere nor other deformations of the painted surface or the substrate has been detected, even under transmitted illumination, which is considered as the most appropriate methodological approach for this kind of investigation.

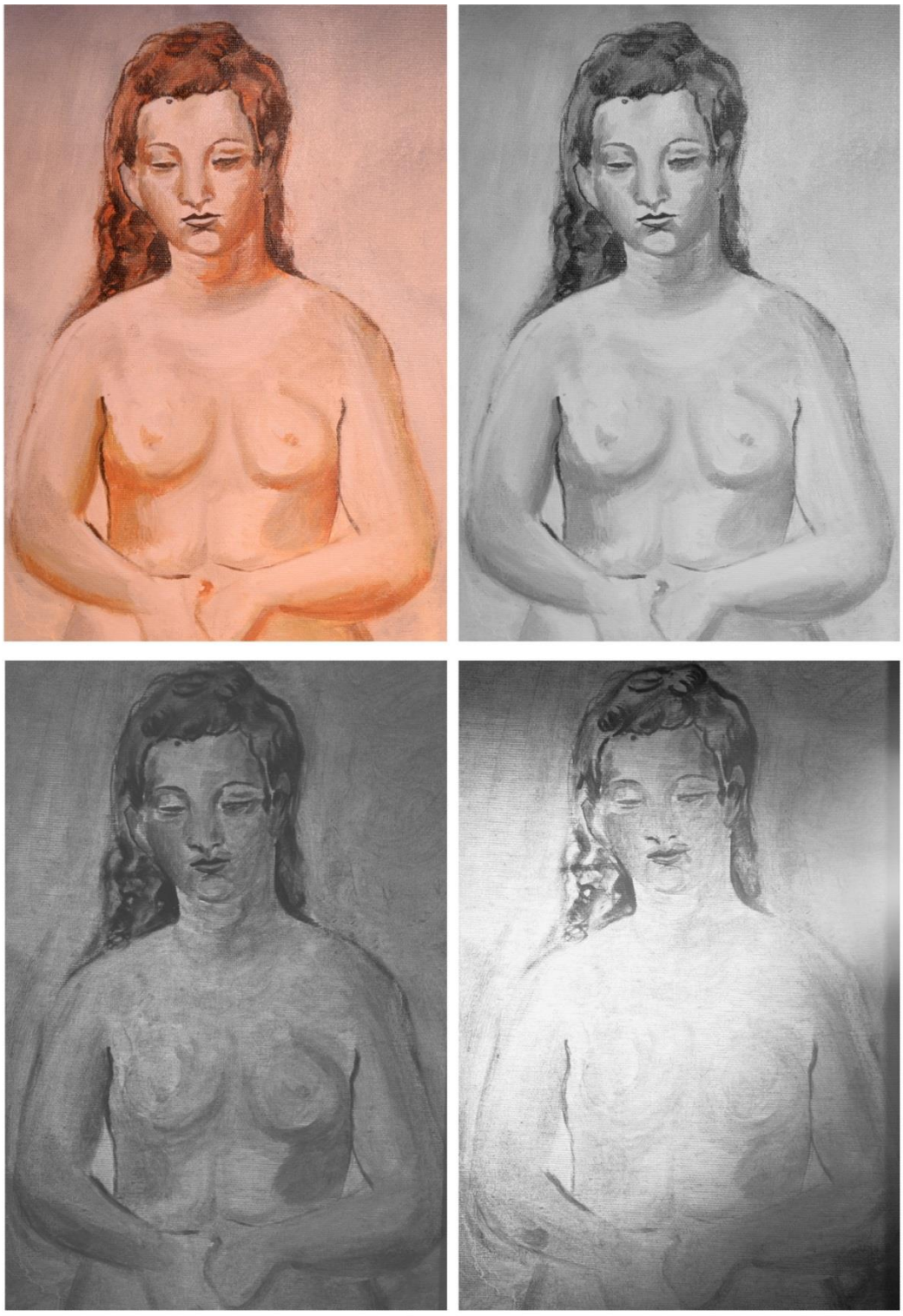


Figure 153: Oil on canvas, replica, front-side, clock wise from top left, digital image (reflected light), digital desaturated image, transmitted IR image and transmitted visible image (Image author's own).

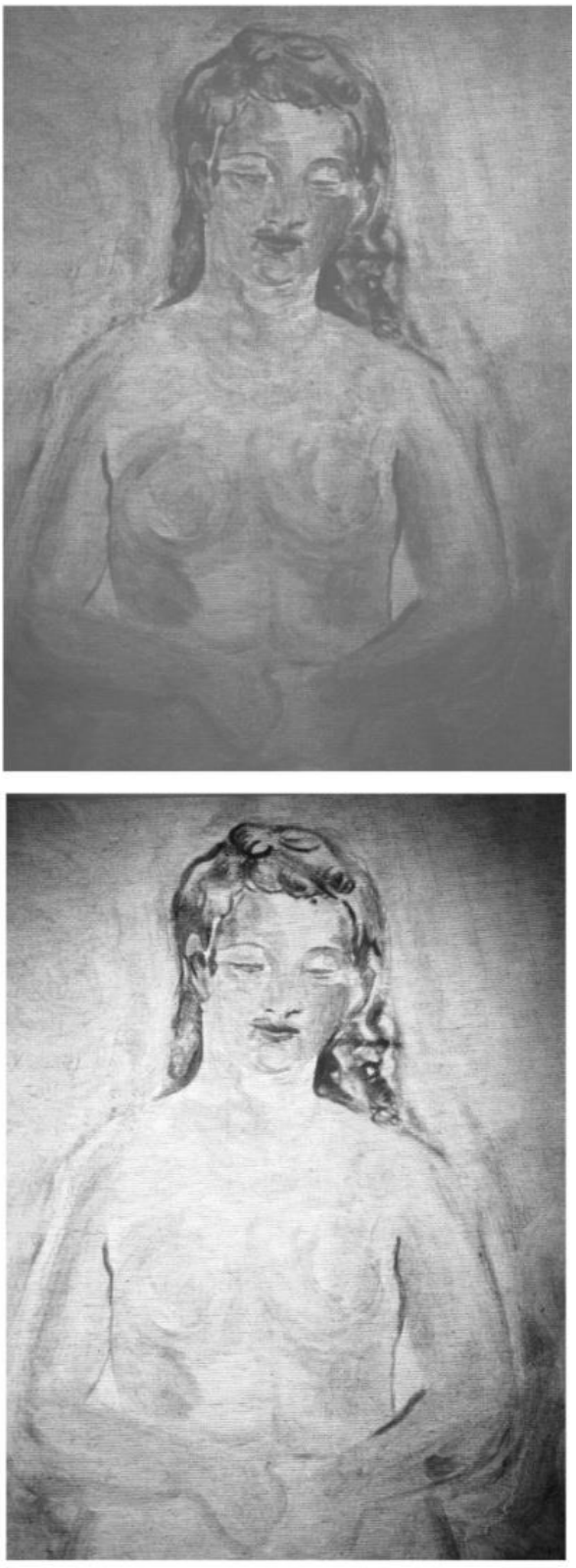


Figure 154: Oil on canvas, replica, backside transmitted visible images (top) and transmitted IR images (below) (Image author's own).

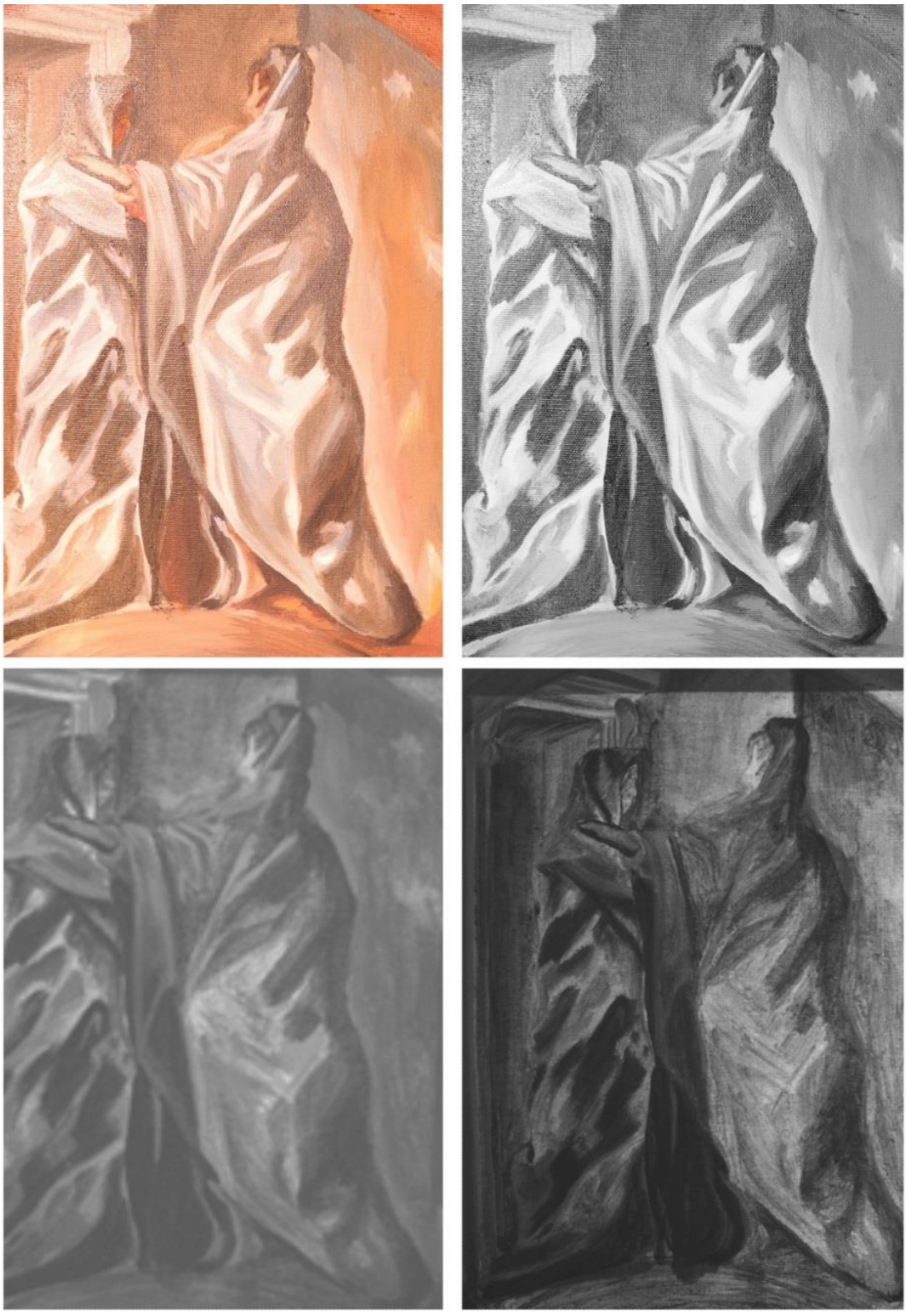


Figure 155: Oil on canvas, replica, backside, digital image, desaturated image, trans-irradiation and trans illumination image (clockwise from top left) (Image author's own).

Normal RTI reveals the surface topography. The dominating feature in the canvas depicting the nude girl is the texture of the canvas, which is clearly visible in RTI visualizations. The stronger strokes are also obvious, such as those in the area of the mouth, and the limited number of brush strokes on the hair, created in different modes in comparison to the rest of the surface (Figures 156-158)[26]. Due to the different response of the pigments in IR radiation, the IR-RTI enables better characterization of areas of the painting and emphasizes preparatory lines, which appear softer in visible RTI. One of the most characteristic examples is the visualization of the lines in the door depicted on the background of the left side of the canvas (Figure 159).

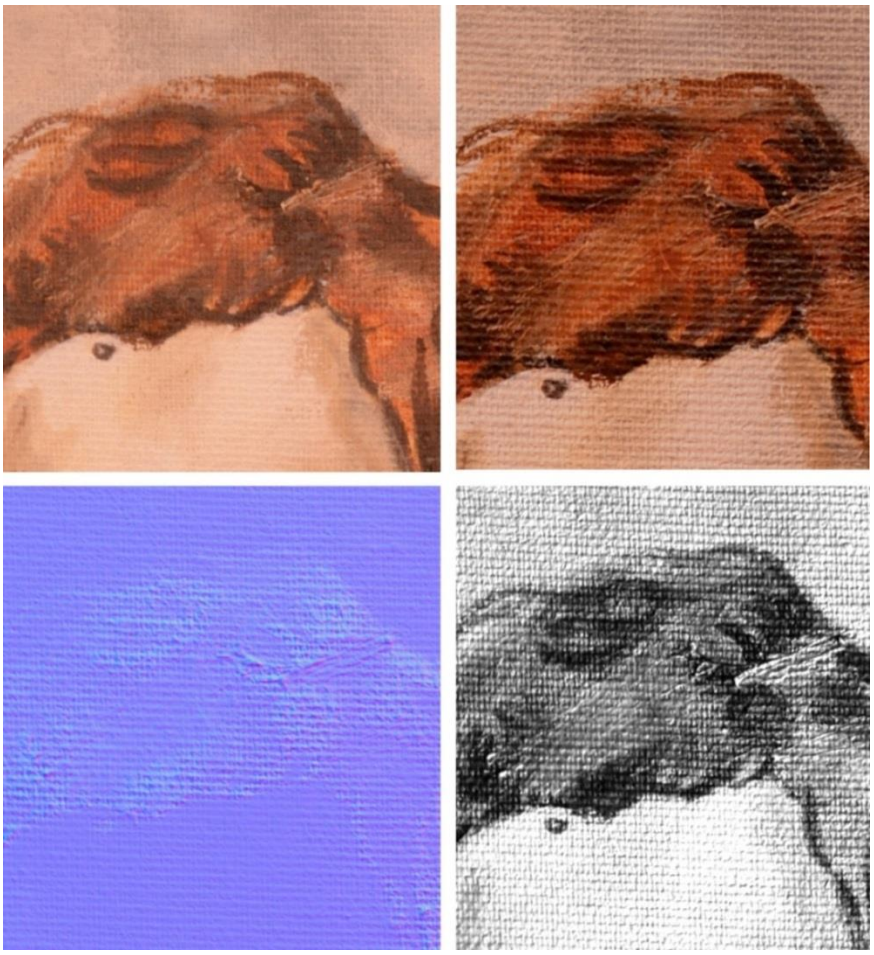


Figure 156: Oil on canvas, replica, detail, digital image (top left) and RTI visualizations (Image author's own).

[26] See Digital Library, folder section5.3, file REP_PCAN_1-VIS_MA_H.rti

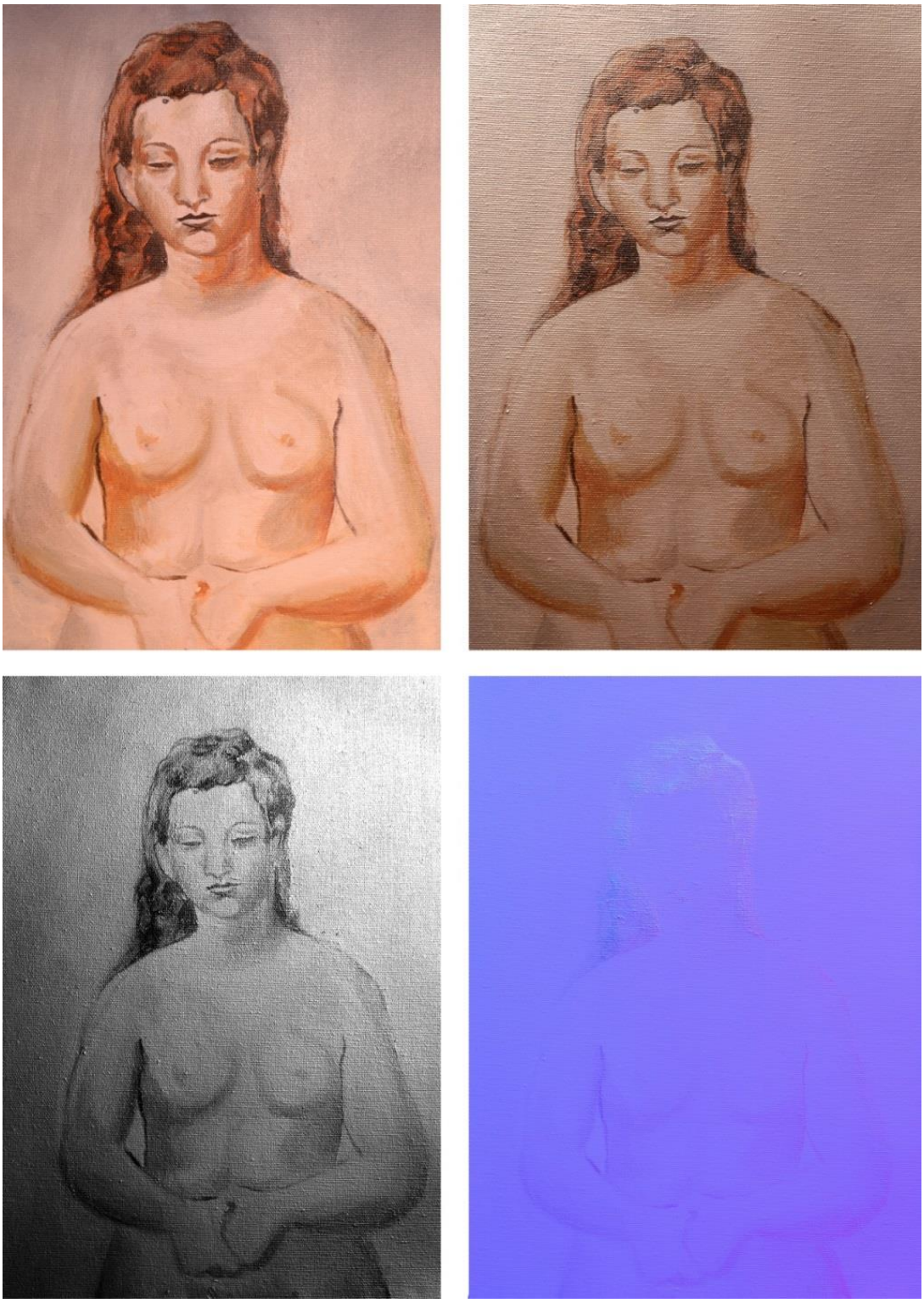


Figure 157: Oil on canvas, replica, digital image, RTI visualization, normal map and RTI visualization in psecular enhancement rendering mode (clockwise from top left) (Image author's own).

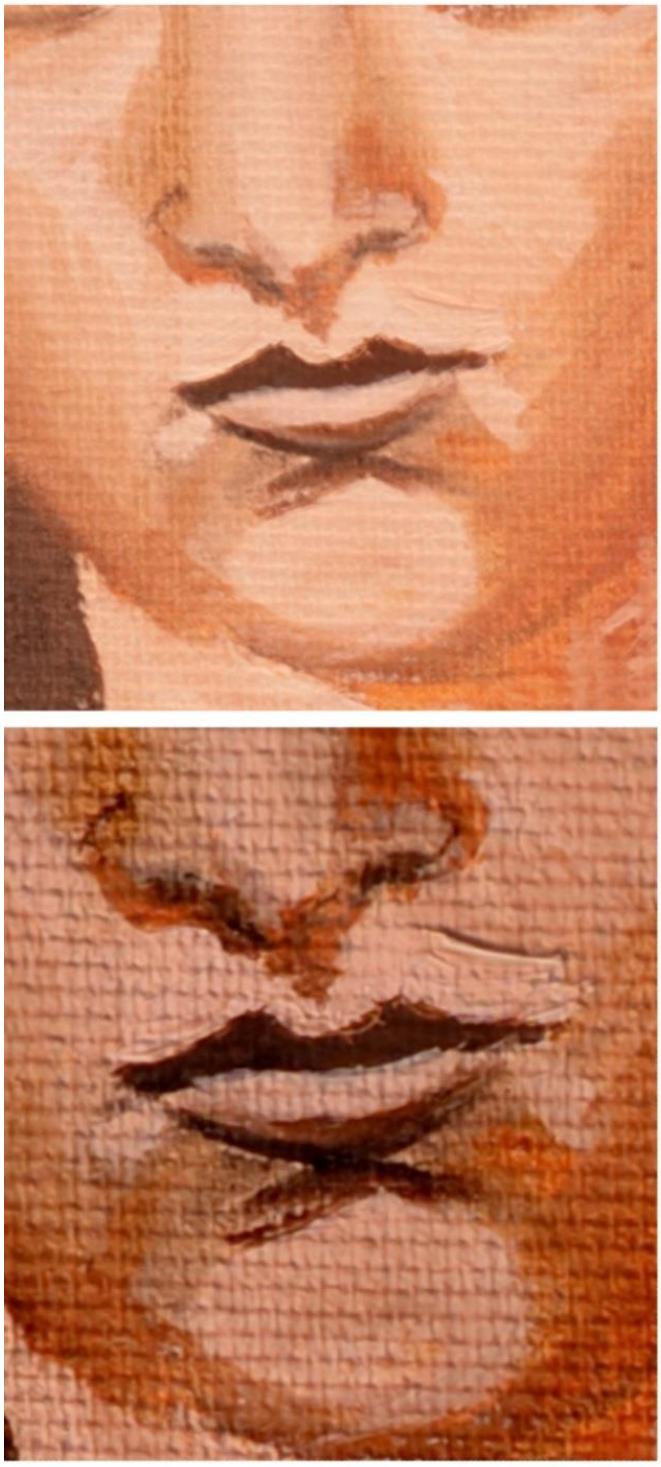


Figure 158: Oil on canvas, replica, detail, digital image (top) and RTI visualization (below) (Image author's own).

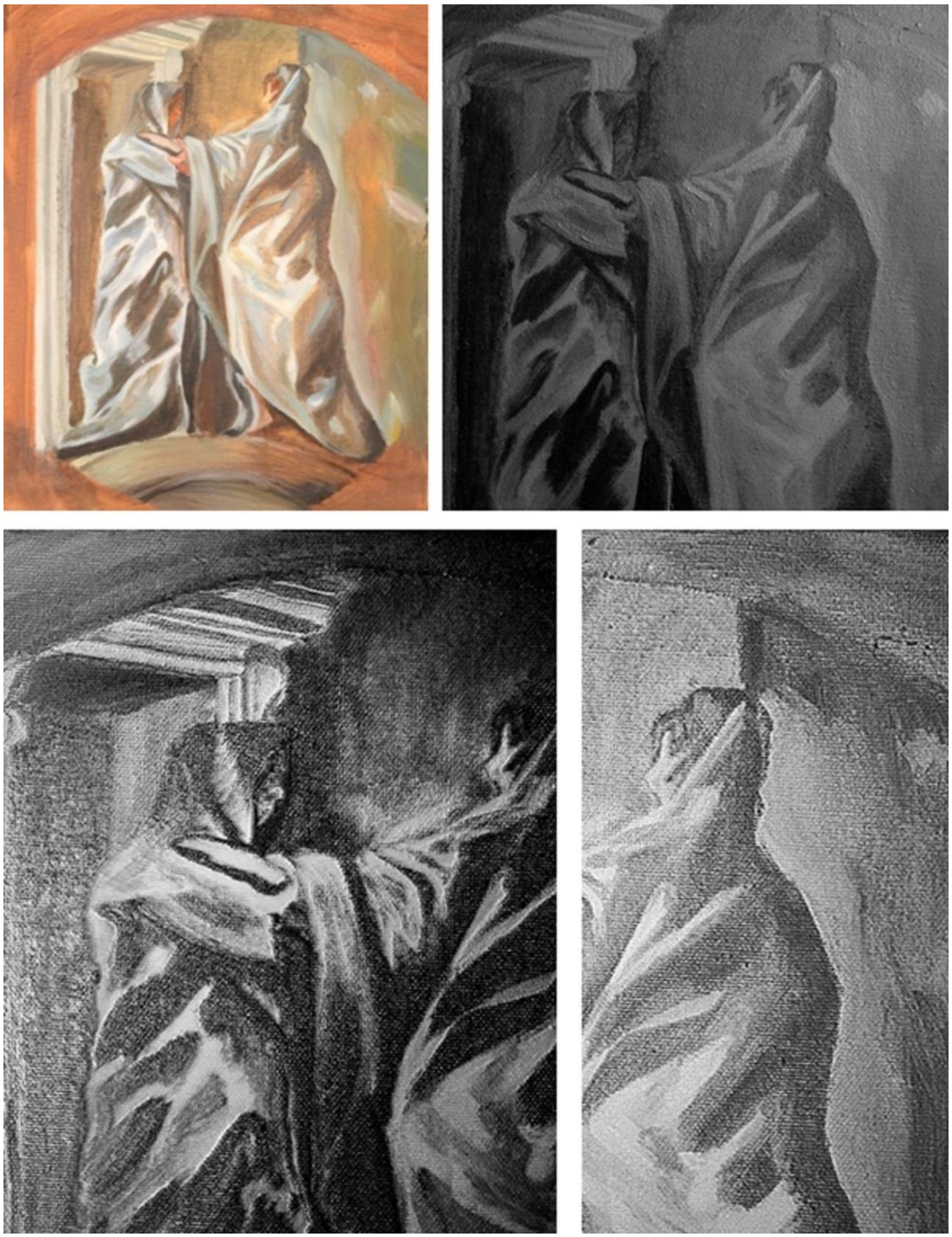


Figure 159: Canvas oil painting, replica. digital image, RTI visualization (up) and IR-RTI visualizations (below) (Image author's own).

In trans illumination RTI the crucial parameter that governs the results is the thickness and the opacity of the painting layer. Its reflectance properties, such as the gloss, affect the results but to a lesser extent. The direction, the shape, the thickness of the painting strokes can be observed. Moreover, conclusions about the materials (tools, mediums, pigments) and the painting techniques can be reached. As the surface is virtually relighted in transmitted mode the areas with the larger quantities of colour applied and the stronger strokes appear not to be differentiated. Instead the areas which present a certain degree of translucency appear more or less lighted, in accordance to the direction and the location of the light beneath the surface under examination. In that way the visual result is differentiated in each trans illumination RTI snapshot, and the viewer experiences the transmittance properties of the surface in a superior way to transmitted imaging, mainly due to the perception of three dimensionality of the painting. This feature can be characterised as a pseudo-three dimensionality of transmitted RTI because the texture revealed does not come in accordance with the actual texture of the surface, but it is the result of the virtual relighting of the translucent areas of the painting. Hence, the pseudo-three dimensionality of transmitted RTI should not be confused with the ability of normal RTI to emphasize textures (Figures 160-162)[27].

In IR-RTI the crucial parameter, in addition to the thickness of the paint layer, is the composition of the pigment[28]. Transmitted imaging in synergy with RTI leads to a better appreciation of the properties of painting techniques. In the transmitted IR-RTI the visualizations produced emphasize the same features as the trans illumination, but are further enriched by the penetrative qualities of IR radiation. The comparison of the visualizations produced from the RTI methodologies reveals the different features of the painting emphasized. The multispectral RTI methodologies, either reflected or trans irradiation, are of great value in terms of diagnostic examination. The reflected IR-RTI emphasizes the texture of the surface beneath the visible and enables the advanced perception of the surface topography. However, the transmitted IR-RTI underlines the basic lines of the drawing enabling an in depth examination

[27] See Digital Library, folder section5.3, file REP_PCAN_1_T-VIS-MA-H.ptm
[28] See Digital Library, folder section5.3, file REP_PCAN_1_T-IR-850-MA-H.ptm

of the application of the colour and providing evidence for the painting history of the artwork. Hence, for a complete RTI visualization of canvas paintings and similar artworks trans illumination and trans irradiation in addition to multispectral imaging is recommended (Figures 163-165).

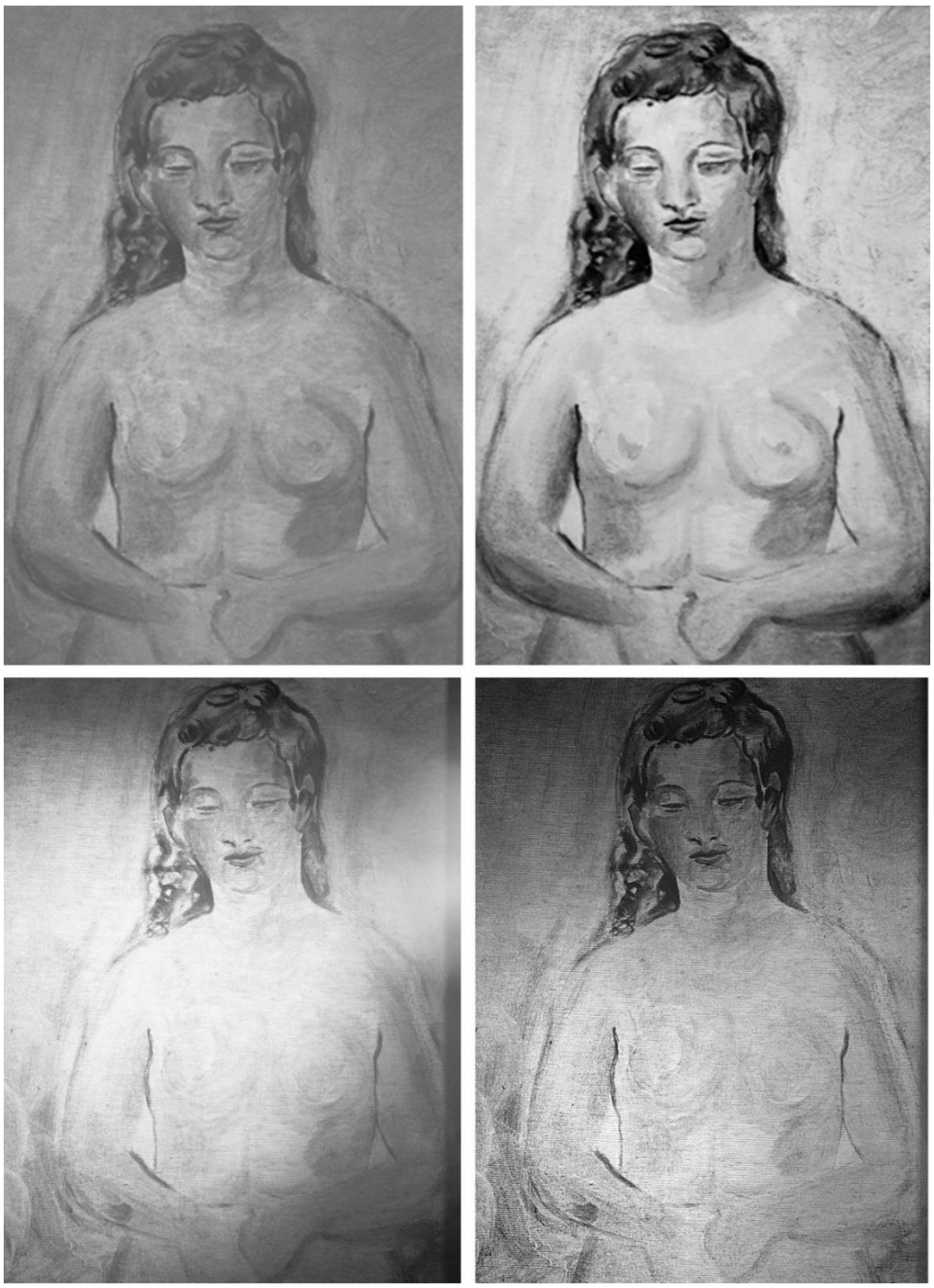


Figure 160: Oil on canvas, replica. Transmitted digital image (top left) and transmitted RTI visualizations (Image author's own).

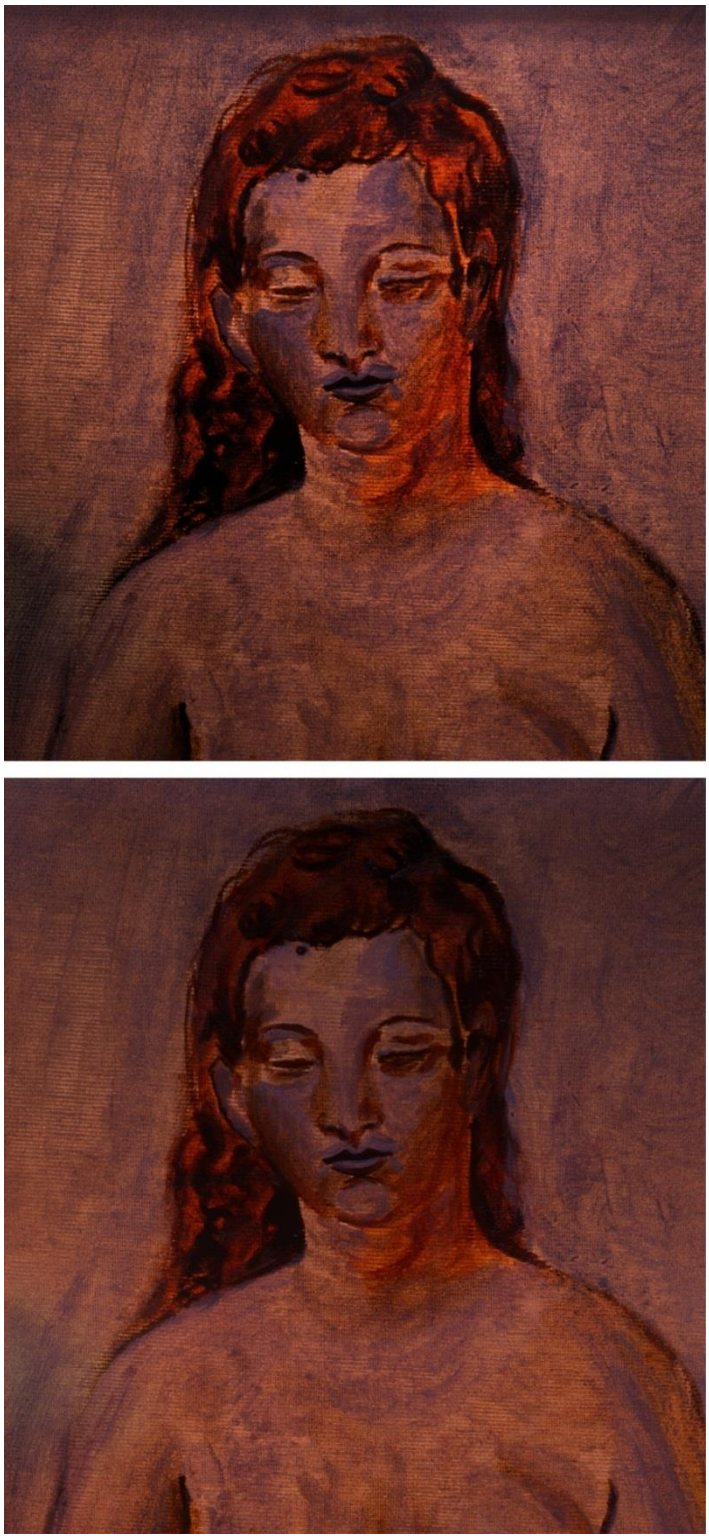


Figure 161: Oil on canvas, replica, detail, transmitted RTI visualizations (Image author's own).

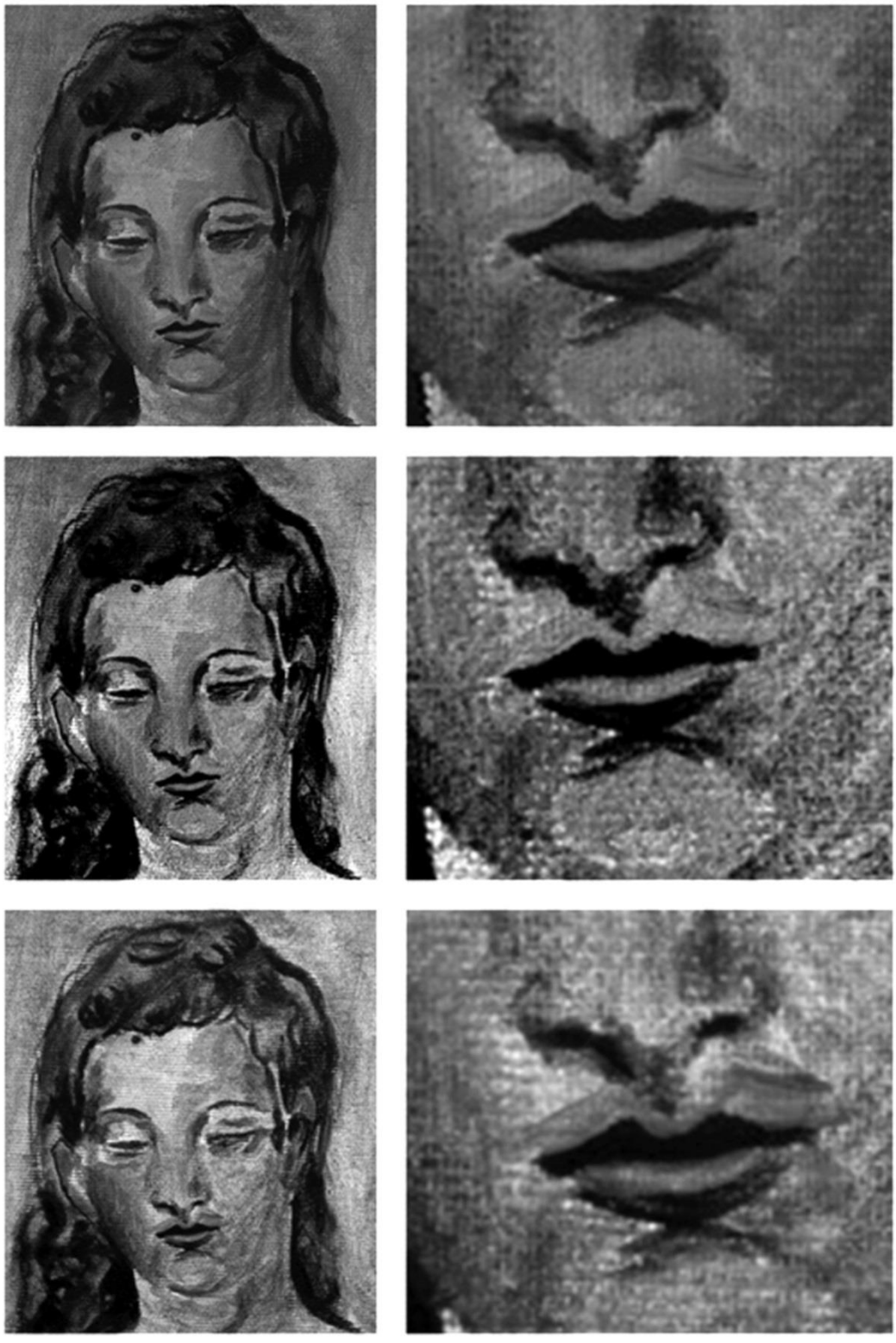


Figure 162: Oil on canvas, replica, detail, transmitted RTI visualizations (Image author's own).

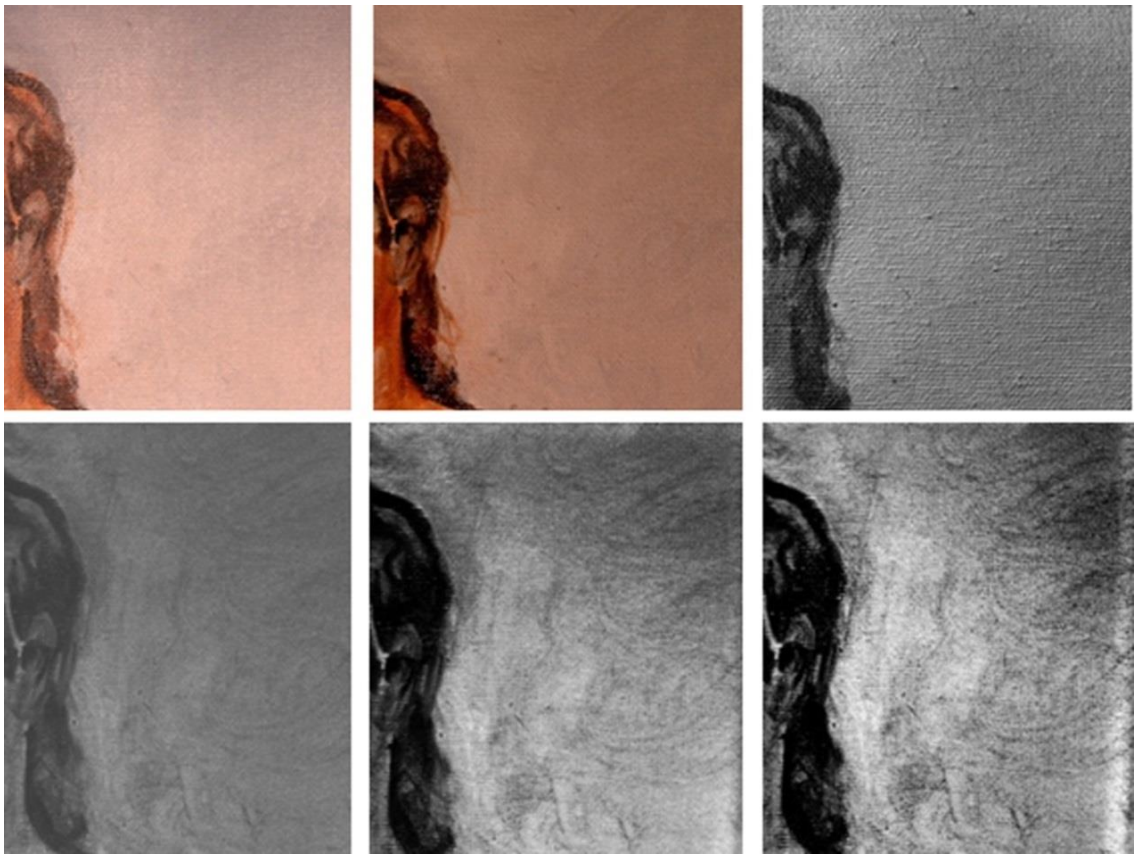


Figure 163: Detail, comparison of reflected and transmitted light digital images (left) and RTI visualizations (middle, right). Digital reflected image (up, left) and normal RTI visualizations (up, middle and right). Transmitted digital image (below, left) and transmitted RTI visualizations (bellow, middle and right) (Image author's own).

Figure 164: Canvas oil painting, replica. Transmitted digital image, transmitted RTI visualization, transmitted IR-RTI visualization and transmitted IR image (clockwise from top left) (Image author's own).

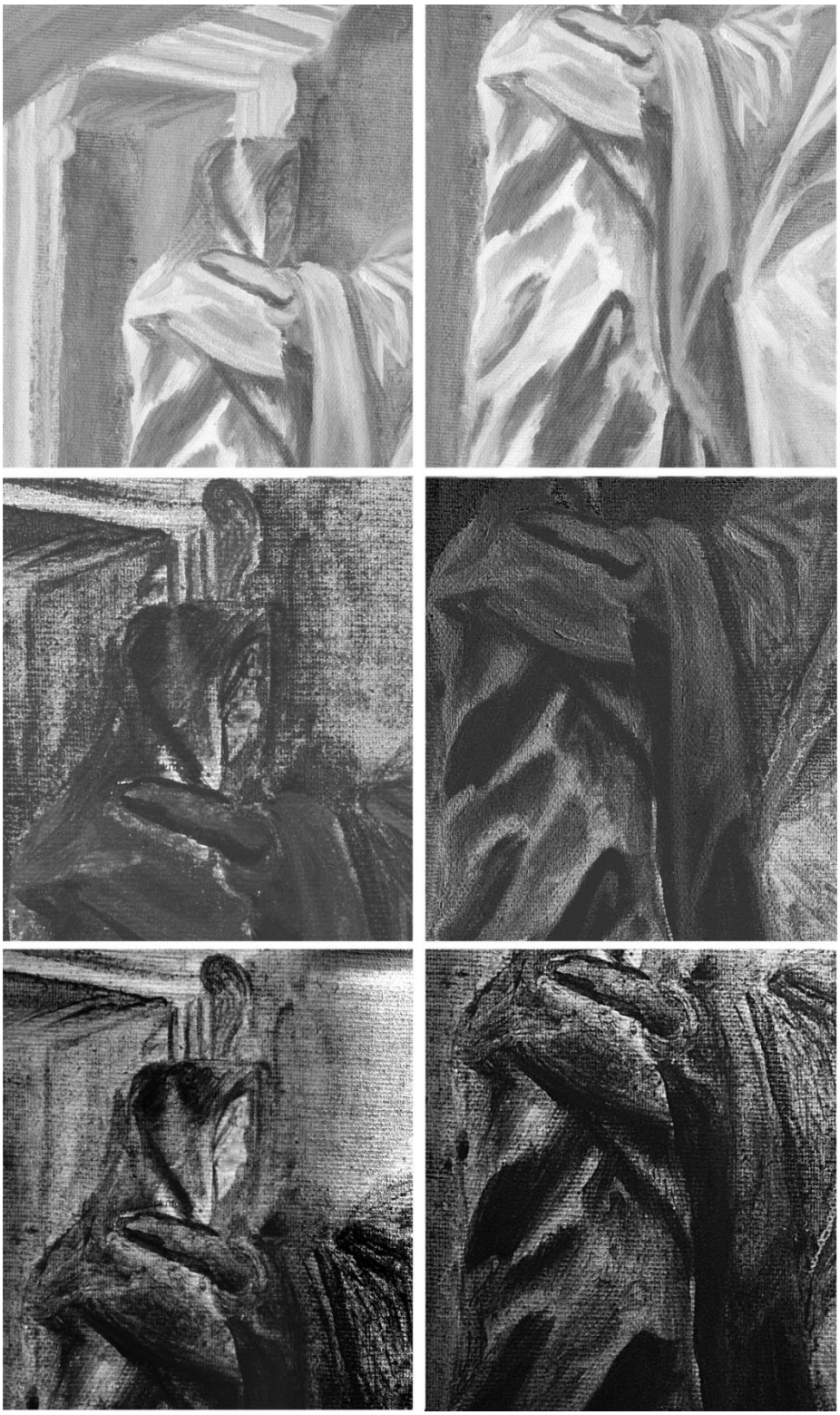


Figure 165: Canvas oil painting, replica. RTI visualizations (top), IR-RTI visualization (middle) and transmitted IR-RTI visualization (below) (Image author's own).

5.3.2.2 Archaeological materials

5.3.2.2.1 Stone

RTI provides an enhanced view of the surface morphology of stone vessels[29]. In the case of the alabaster alabastron B61, it enables advanced examination of the morphology of the base of the vessel, emphasizing its shape (Figure 166). Undoubtedly, our knowledge about manufacturing techniques can be enhanced through the study of the surface morphology because striations, either interior or exterior, are important evidence of manufacture techniques. Consequently, the large numbers of parallel lines on the exterior of the alabaster, which is difficult to see under normal light because of the low relief and the deterioration effects revealed through RTI, are important evidence of the technology of manufacture. Also, the inscription KY is emphasized (Figure 167). Fragments of the vessels' bodies discovered in Tomb A, which present a variety of preservation, were examined with the macroscopic highlight RTI method, which enable enhanced visualization of the surface deformation and damage, such as alterations, salt efflorescence and discoloration (Figures 168-169). In the case of small fragments of approximately 1 cm, microscopic dome RTI proved useful for the examination of minor details. The most interesting examples were the visualizations of the handles, which reveal their morphology and tool marks (Figure 170).

Figure 166: Alabaster alabastron, Derveni Tombs, B61. Archaeological Museum of Thessaloniki Digital image (left) and RTI visualization of the base (right) (Image author's own).

[29] See Digital Library, folder section5.3, files AMTH_GR_ALA_A84_VIS-MI-MD1.rti and AMTH_GR_ALA_B61_VIS-MA-H.rti

Figure 167: Alabaster alabastron, Derveni Tombs, B61. Digital image of the vessel's upper body (left) and RTI visualization (right) (6,6 cm length) (Image author's own).

Figure 168: Alabaster alabastron, Derveni Tombs, A84 (0.086 m length). Archaeological Museum of Thessaloniki. Digital image (top) and RTI visualizations of details (below) (Image author's own).

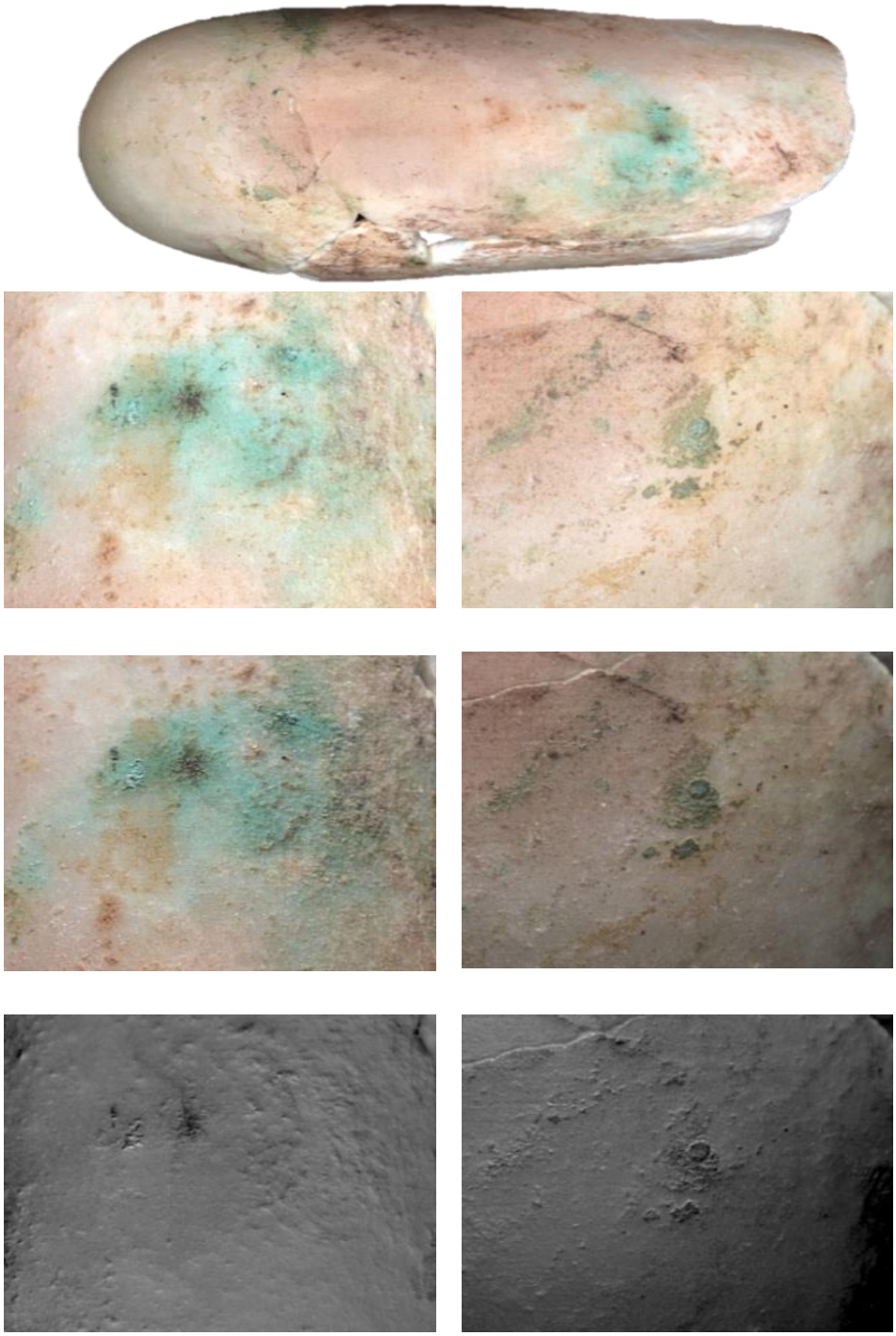


Figure 169: Alabaster alabastron, Derveni Tombs A84 (0.09 m length). Archaeological Museum of Thessaloniki. Details of encrustations and decolouration areas. Digital images (top) and RTI visualizations (middle, below) (Image author's own).

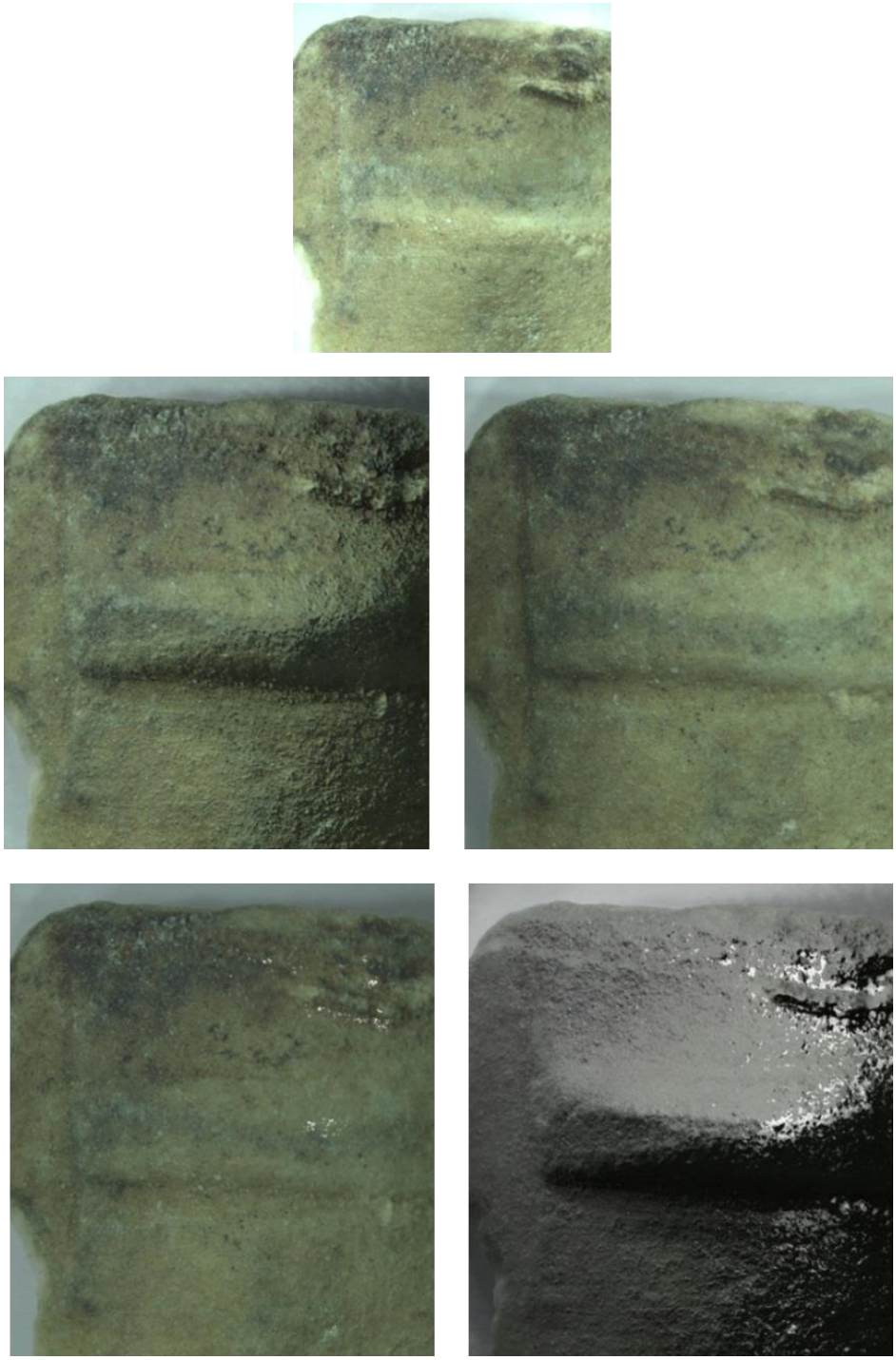


Figure 170: Alabaster alabastron handles, Derveni Tombs, from group A84, detail 1cm. Archaeological Museum of Thessaloniki. Digital image (left) and RTI visualizations (middle, right) (Image author's own).

5.3.2.2.2 Glass

The advanced visualizations of surface anomalies in the case of the glass vessels indicate RTI's efficiency in condition reporting[30]. RTI visualizations of two restored glass alabastra reveal excessive restoration treatment, emphasizing areas where the filler covers the original material (Figures 171-172). As well, the yellow and white glass thread used for the dense feather decoration pattern and other surface irregularities, such as cracks and losses, can be documented via RTI (Figures 173-174). In addition, RTI emphasized surface details and provides support for proposed methods of fabrication (Figure 175). A characteristic example is the correlation of the fabrication techniques to the surface appearance of glass and its degradation phenomena. In this case study the use of granulated glass is confirmed by RTI visualizations.

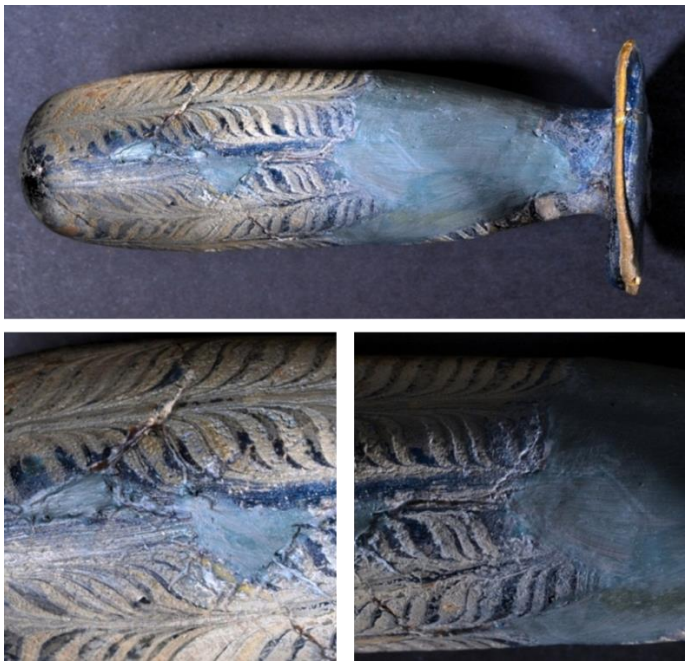


Figure 171: Glass alabastron, Derveni Tombs D31. Archaeological Museum of Thessaloniki. Digital image (top) and RTI visualization of details (below) (Image author's own).

[30] See Digital Library, folder section5.3, files AMTH_GR_GL_D32a_VIS-MA-H.rti and AMTH_GR_GL_D32b_VIS-MA-H.rti

Figure 172: Glass alabastron, Derveni Tombs D31. Digital image (up) and RTI visualization of details (down) (Image author's own).

Figure 173: Glass alabastron, D32. Digital image (up), RTI visualization (below) (Image author's own).

Figure 174: Glass alabastron, D32. Digital image (up) and RTI visualization of details (down) (Image author's own).

Figure 175: Glass alabastron, D32. RTI visualization of loss and pitted surface (Image author's own).

5.3.2.2.3 Mortars

Through RTI irregularities, related to degradation, encrustation, depositions, losses and cracks can be documented, as demonstrated by the comparison between PTM and standard computer graphic approximation (Figure 176). RTI is a tool for the exploration of stratigraphy, even in cases of badly deteriorated fragments. Also, RTI can provide an insight into painting techniques as colour application can be studied in detail non-destructively and more efficiently than traditional techniques (Figure 177). Details, such as the fingerprints marks on the surface of a ceramic roundel attached to the wall painting fragment, are revealed (Figure 178)[31].

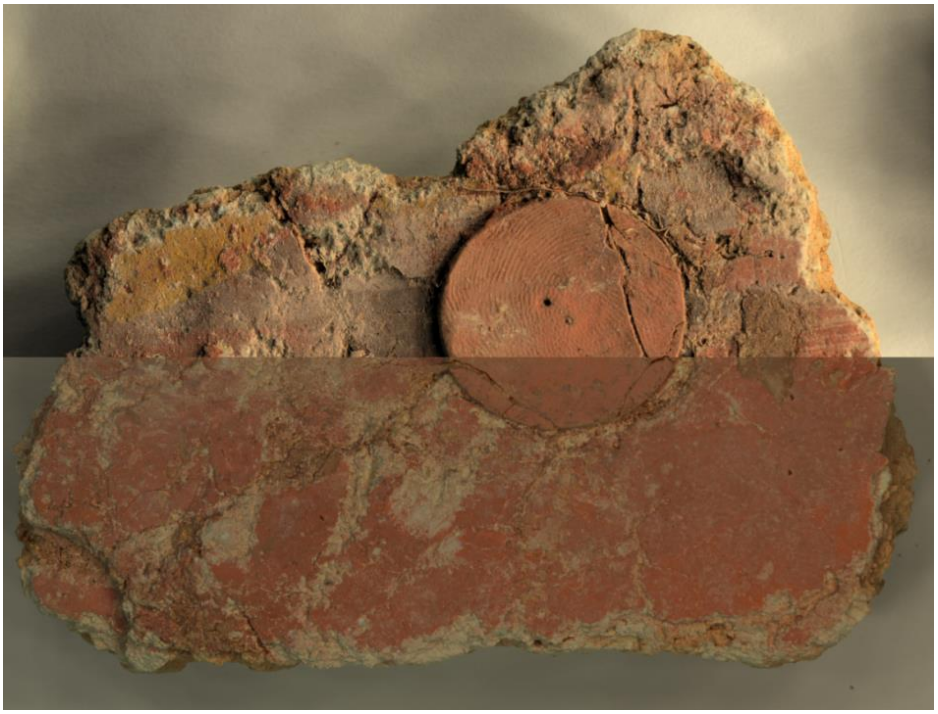


Figure 176: Wall painting fragments, Z42. 10cm length. Comparison between PTM (top) and a standard computer graphic approximation (below) (Image author's own).

[31] See Digital Library, folder section5.3, file AMTH_GR_MOR_Z42_VIS-MA-H.rti

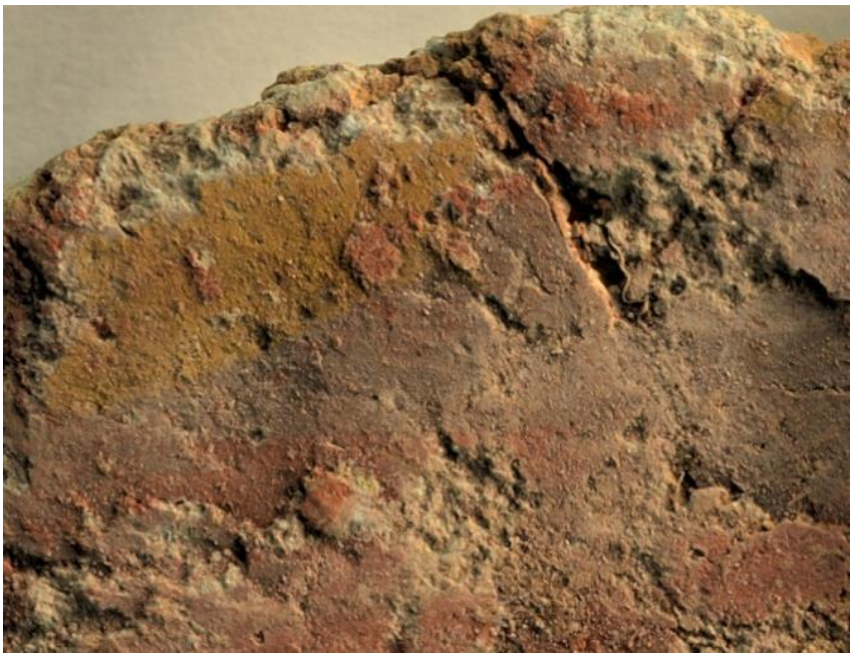


Figure 177: RTI visualizations of detail (Image author's own).

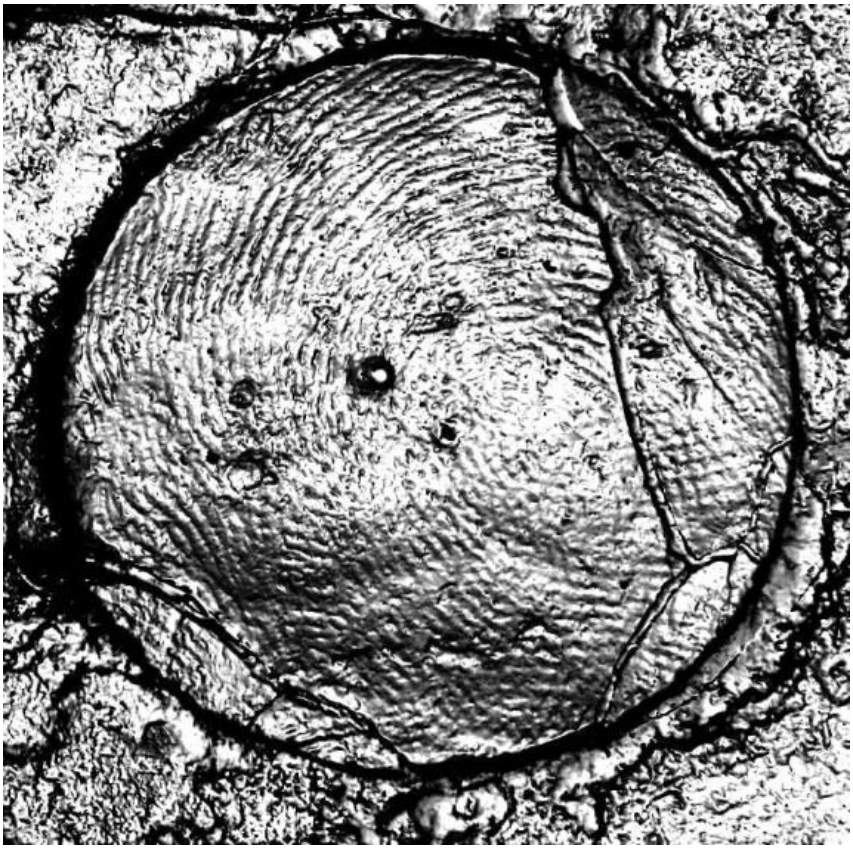


Figure 178: Details of the fingerprints, RTI visualization (Image author's own).

Infrared imaging of fragments from wall-paintings from tombs Z and B leads to interesting results. In the reflected infrared image at 720 nm and above a sufficient amount of visible light is detected. As a result the label is visible in this low intensity IR image, while it disappears at 860 and above. The response of blue colour is similar to that of the white at 760 nm and above, but it is highly differentiated at 950 and above. In case of the highly deteriorated fragments, the presence of depositions and colour losses result in low contrast images under IR radiation. Moreover, FCIR imaging enables initial material characterization, indicating that the blue pigment used form the ancient painter of the Derveni Tombs was Egyptian blue (Figures 179-181). The IR-RTI provides an insight into the texture of the wall painting fragments without the obscuring encrustations visible under normal illumination but invisible under infrared radiation. Notable are the clearer visualization of the substrate and the differentiation of colours (Figure 182-183)[32].

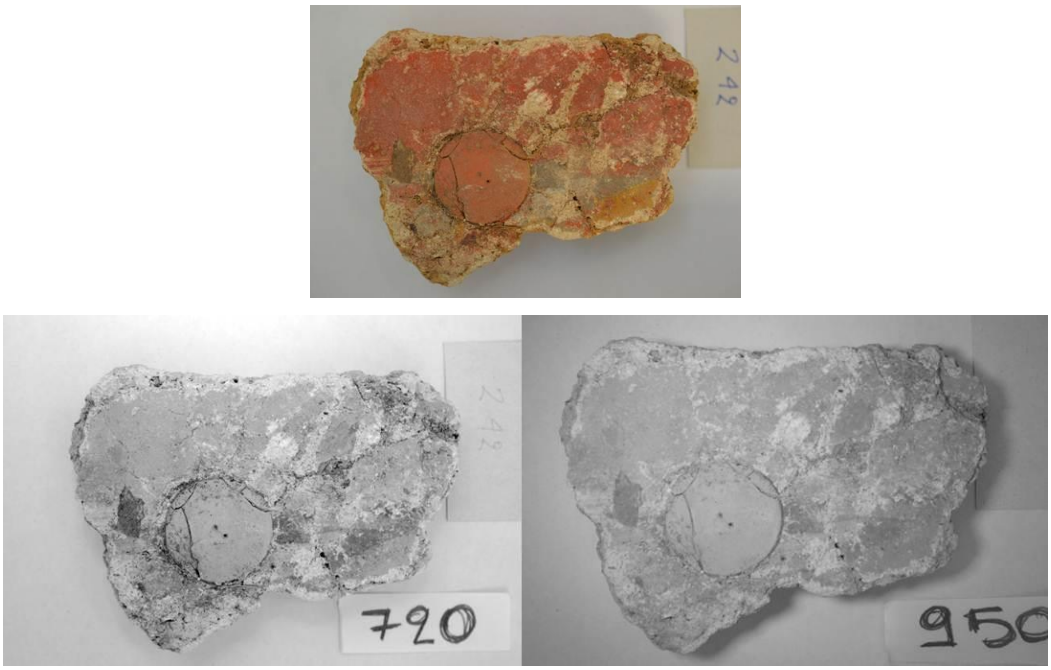


Figure 179: Wall painting fragments Z42, digital image (top), IR images at 720nm (below left) and 950 nm (below right) (Image author's own).

[32] See Digital Library, folder section5.3, files AMTH_GR_MOR_Z42_IR-950-MA-H.rti and AMTH_GR_MOR_Z42_IR-760-MA-H.rti. For comparisons see the RTI file in the visible area file AMTH_GR_MOR_Z42_VIS-BW-MA-H.rti

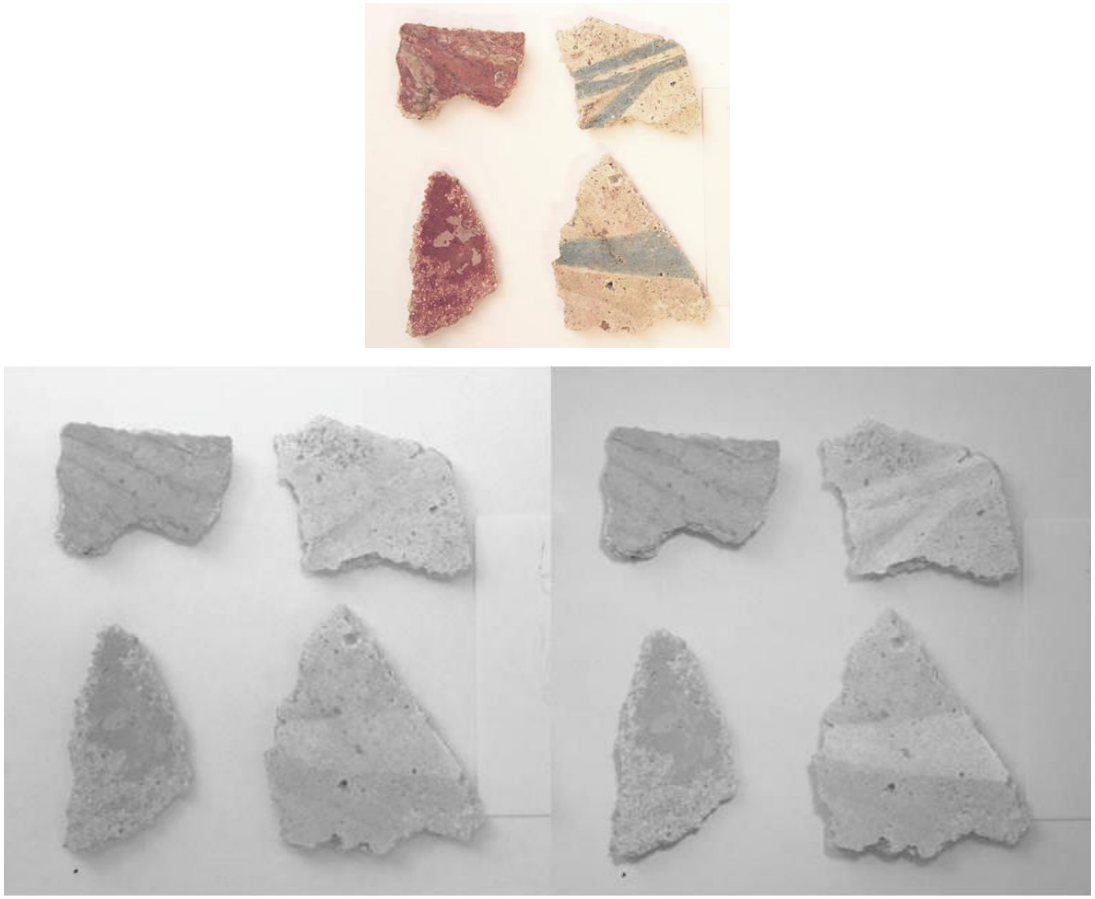


Figure 180: Wall painting fragments B108, digital image (top), IR images at 760nm (below left) and 850 nm (below right) (Image author's own).

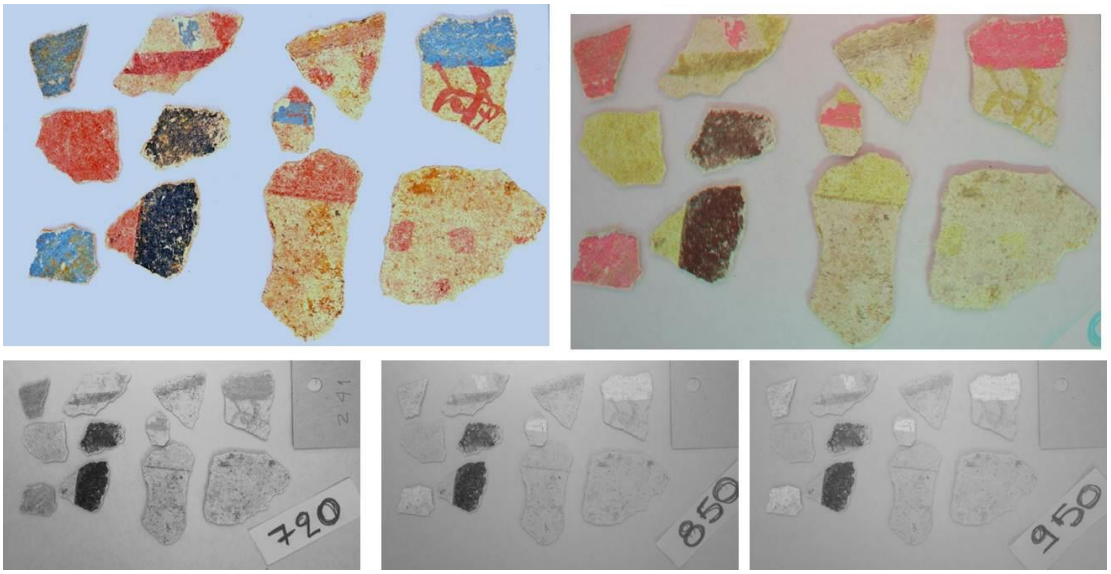


Figure 181: Wall painting fragments Z41, clockwise from top left, digital image, FCIR image, IR images at 950 nm, 850 nm and 720 nm (Image author's own).

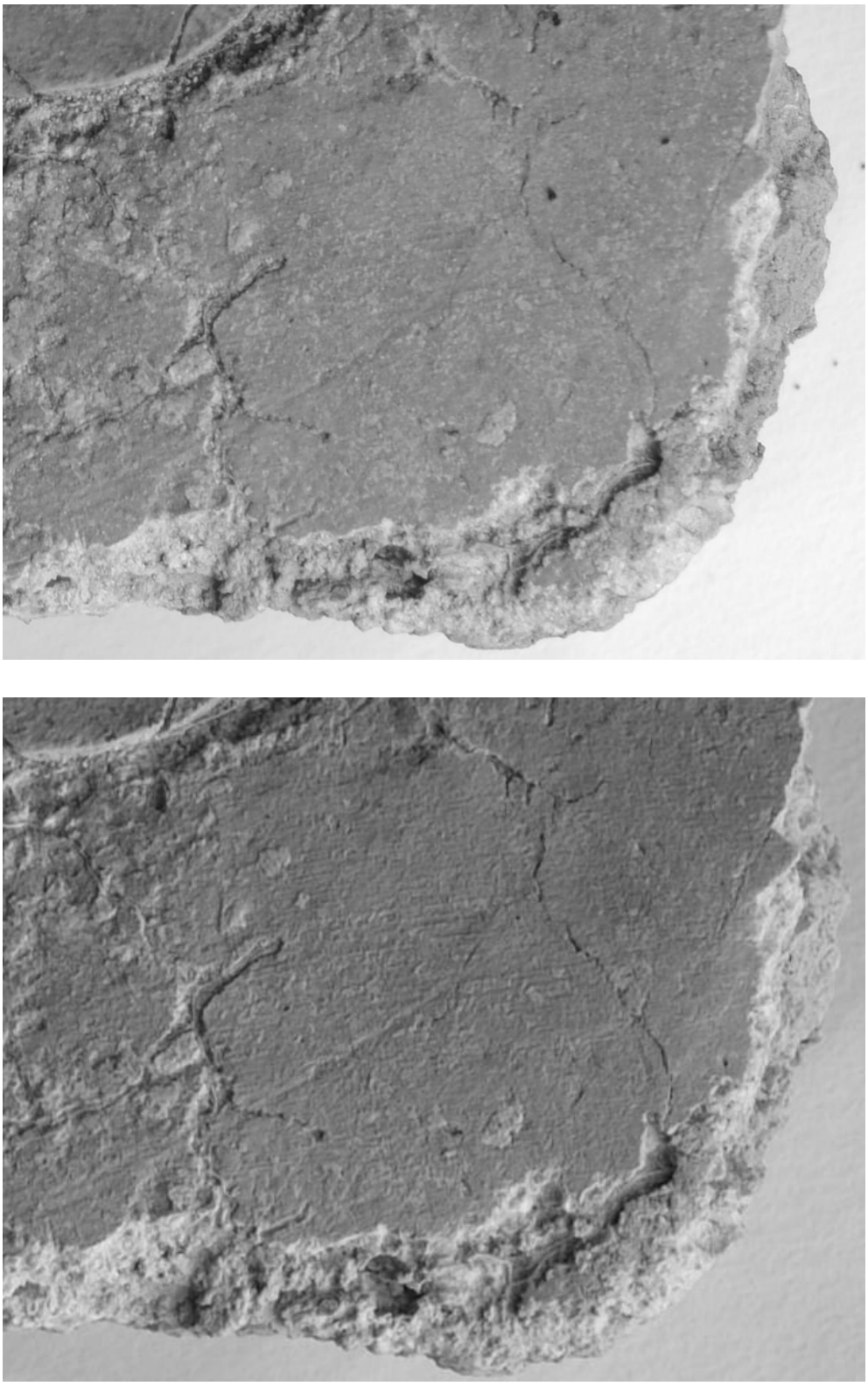


Figure 182: Comparison of visible (top) and IR-RTI Visualization (below) (Image author's own).

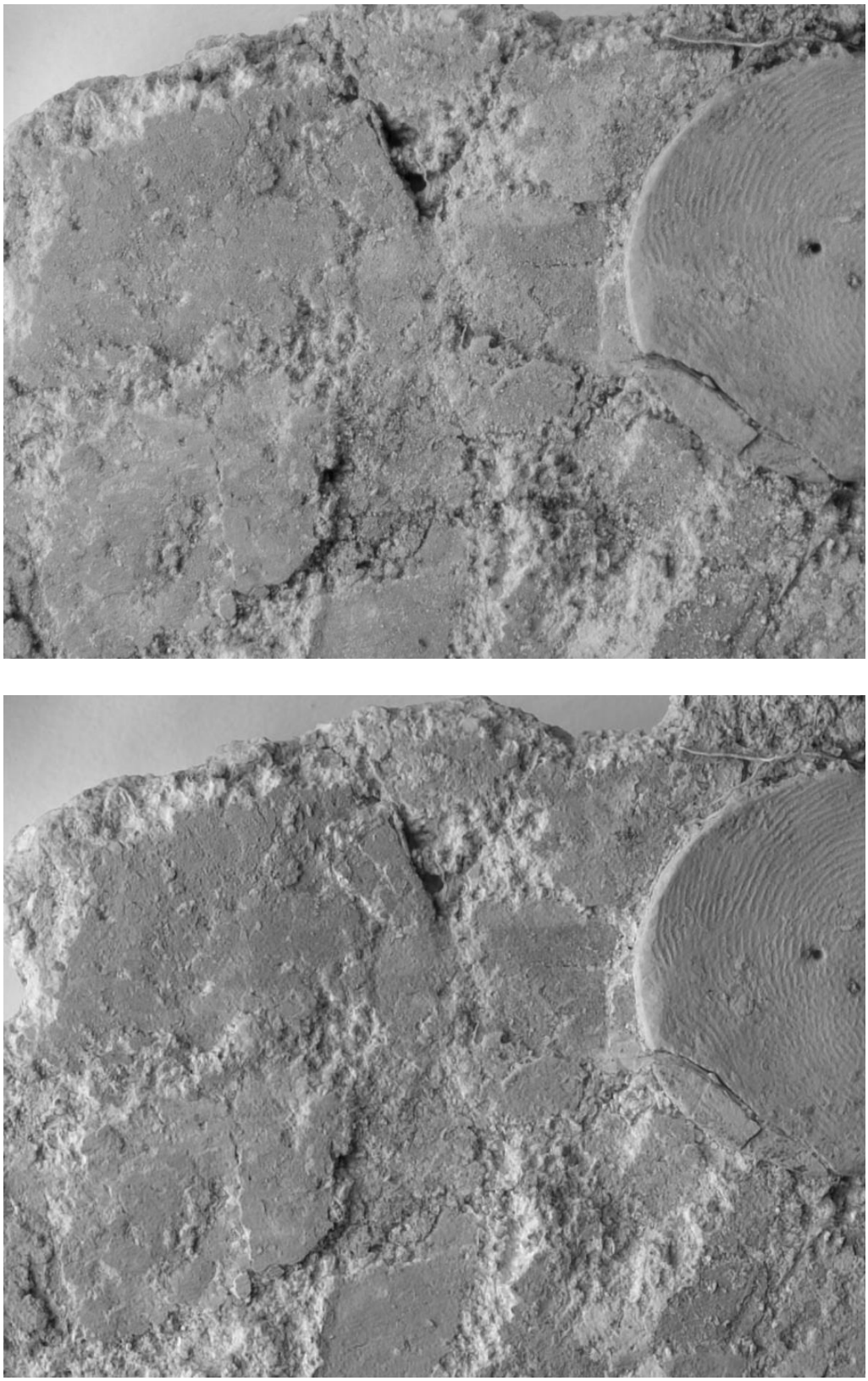


Figure 183: Comparison of visible (top) and IR-RTI Visualization (below) (Image author's own).

5.3.2.2.4 Ceramics

RTI is an enhanced documentation technique for ceramic vessels. Previous treatment, gap-filling, crumbling material, rough surface finish with scratches, pits and losses are documented, assisting in condition reporting. The signs from the wheel, and in the case of black glazed pottery the strokes from the additions of the glaze, can be examined (Figure 184), but undoubtedly the most important contribution of RTI refers to vessels with painted and/or incised decoration, because of their complex surface topography. For that reason west-slope, red-figure, gnathian and Faenza maiolica vessels have been examined.

Figure 184: Black-glazed ceramic skyphos Z29. Diameter 0.078 m. RTI visualizations (Image author's own).

Two West Slope vessels in fragmentary state, a skyphos (C3e) and a kylix (C3th II) were visualised in RTI form at macroscopic and microscopic scale. The state of preservation of the paint decoration was poor, although the pattern was still recognizable. Even in cases of total loss, colour remained as a ghost on the surface of the glaze. RTI offered an insight into the West Slope decoration technique, and enables the advanced study of relief detail by emphasizing even on minor surface variations. Barely recognizable remains of colour, areas where colour had been either totally or partially lost, were highlighted. Moreover, in the case of yellow-tan details, the relatively thick colour used in comparison to the white became obvious in the RTI visualizations, providing evidence for Cook's explanation about Greek vase painting (1997). A few potters' tools are known, mainly the scraper, shaper, severing and measuring tools (Schreiber, 1999). Via RTI the shape and morphology of the different textures created by different tools and tool marks can be studied, providing evidence for the vase construction and decoration techniques used. Macroscopic RTI visualizations in our study revealed a number of incisions and emphasized adjacent concavities on the lower part of the body of the skyphos (black arrows). In the kylix RTI emphasized a surface anomaly under the rim, possibly created by the fingers of the potter or by a sponge (Figure 185).

Microscopic RTI enables the study of the shape of these incisions and can help define tool marks. For example, the microphotograph revealed the presence of 4 lines in the central motif of the skyphos, whilst microscopic RTI visualizations enable the characterisation and further study of these lines. All of them were shown to be incised, with the three lower ones also painted. The salt efflorescence, the small pits and the remnants of colour from the leaves on the surface complicate the study of the tool marks in the two lower incisions. There is no doubt that they were made with circular scrapers, though for the lower one was made a large tool. Both of them were rigid, considering that the width of the incisions is the same. From the horizontal lines on the inside of the incisions one can assume that the tools' surfaces were not very smooth. The upper incision is made with the edge of a sharp rigid scraper, while the second is larger and must have been made with a similar tool, but with stronger incision by the potter's hand (Figure 186).

The triangular tool used for the incisions of the kylix is easily detectable in the microscopic RTI visualizations, and the orientation of the potter's hand direction can be identified. In both vessels the yellow leaves' additions were the last step, usually covering other details of the decoration (Figure 187). Application of RTI and micro-RTI indicated that RTI is an excellent tool for the revelation of incised and painted decoration of West Slope wares, and also assisted in condition assessment. Scratches on the surface, flaking of the glaze and other alterations and damage were easily recognizable.

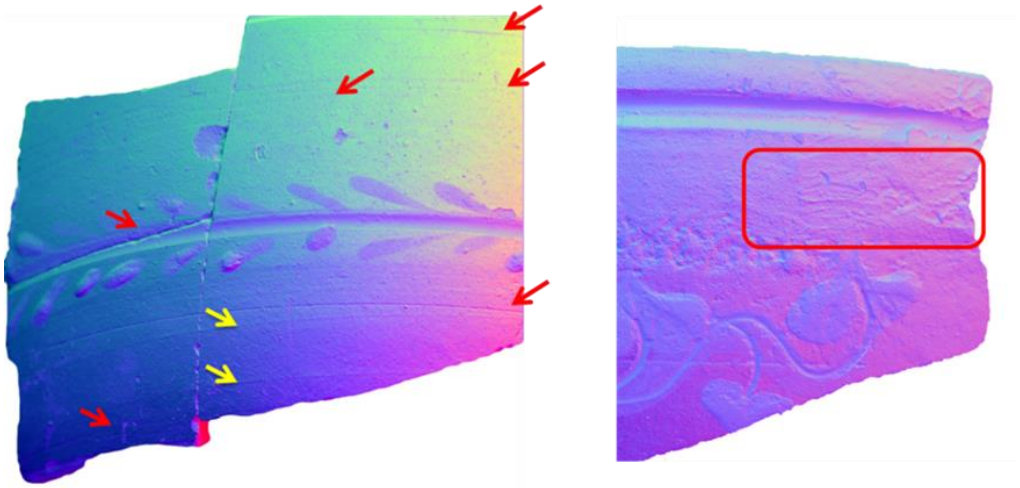


Figure 185: Macroscopic H-RTI visualizations of west slope ceramic fragments from Derveni, fragment from skyphos (3cm across) with emphasised incisions (red arrows) and adjacent concavities (yellow arrows) (left) and fragment from kylix (2cm across) with emphasized a surface anomaly under the rim, possibly created by the fingers of the potter or by a sponge (right) (Image author's own).

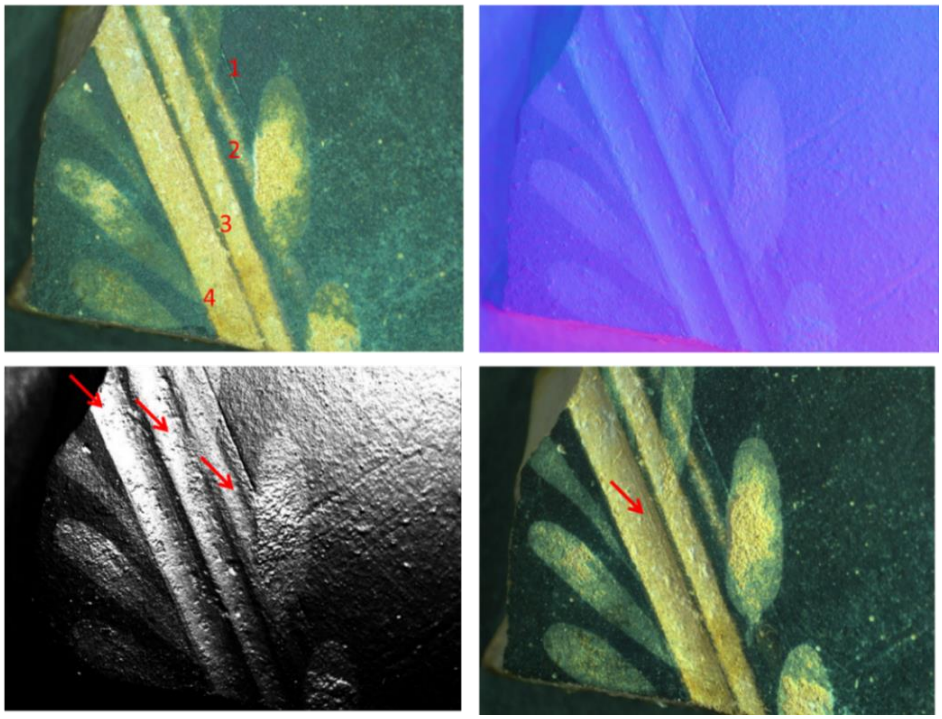


Figure 186: Fragment of the skyphos C3e (0.8cm across), clockwise from top left, microphotograph, normal map, and RTI visualizations (Image author's own).

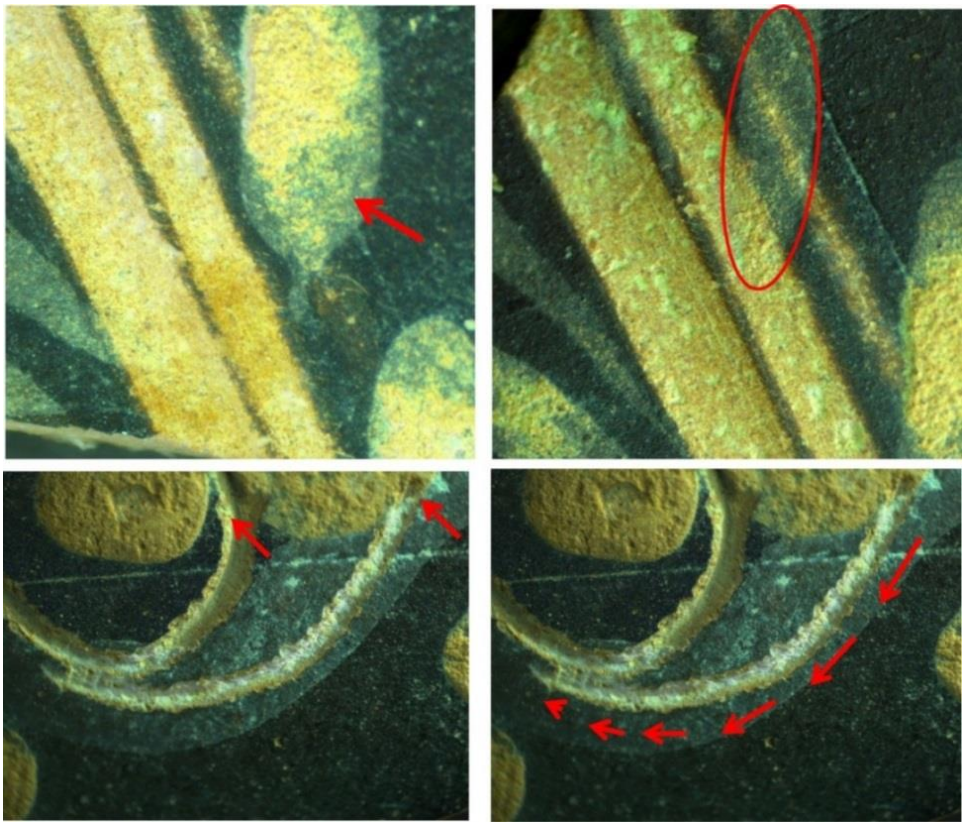


Figure 187: Fragments of the skyphos C3e (top) and cylix C3th II (bottom), microscopic RTI visualizations (Image author's own).

RTI proved a valuable tool for the examination of the red figured technique vase painting technique. Painting techniques can be examined, such as relief lines, outlines, sketch lines, raised dots, and remnants of the black glaze (Figures 188-191). The texture is underlined, including features of extreme importance, such as surface damage losses, scratches, pits, alterations, discontinuities of the paint and the glaze, craqueleure and depositions (Figure 192). Manufacture evidence can be investigated, such as incisions from the ceramic wheel and lines of the preparatory drawing (Figure 193).

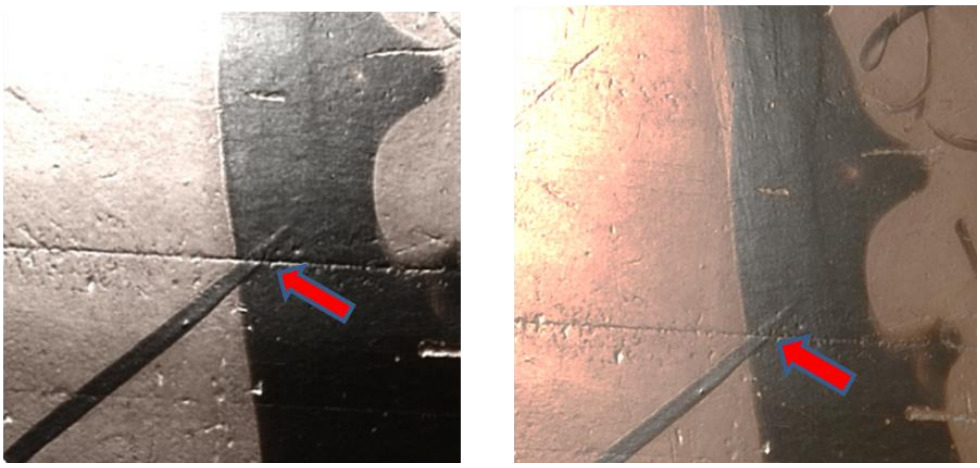


Figure 188: Red figure pelike, C1. RTI visualizations revealing a relief line passing over the black background (Image author's own).

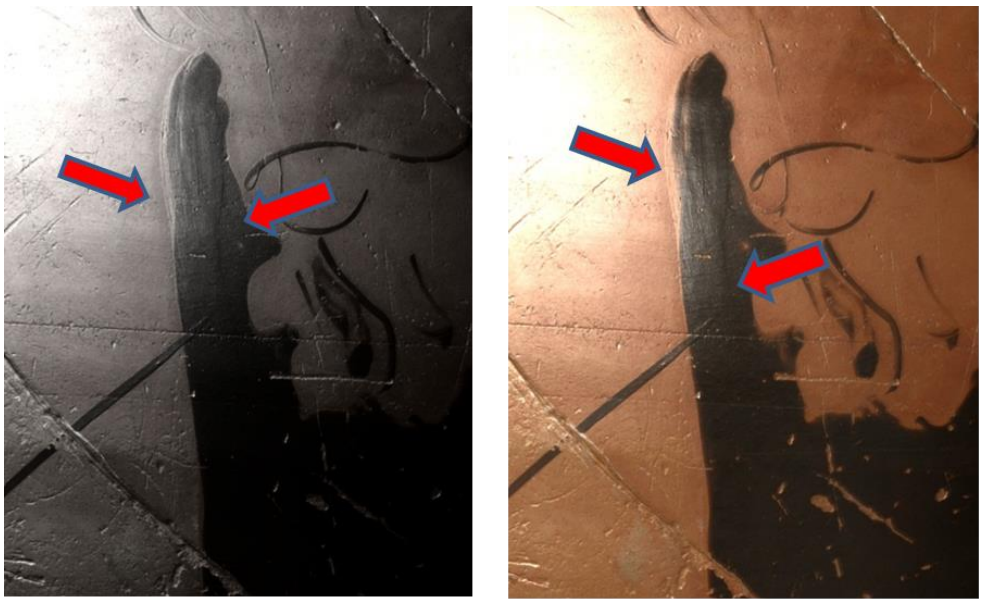


Figure 189: Red figure pelike, C1. RTI visualizations revealing the outline and black glaze brush strokes (Image author's own).

Figure 190: Red figure pelike H2. RTI visualizations emphasizing the outlines of the human figure (Image author's own).

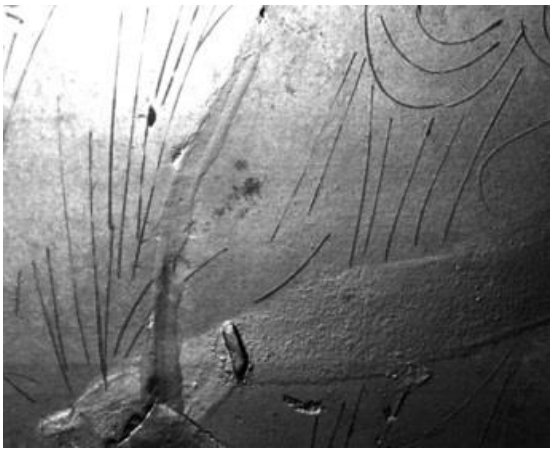


Figure 191: Red figure pelike H2. RTI visualizations underlining the three-dimensionality of the relief lines (Image author's own).

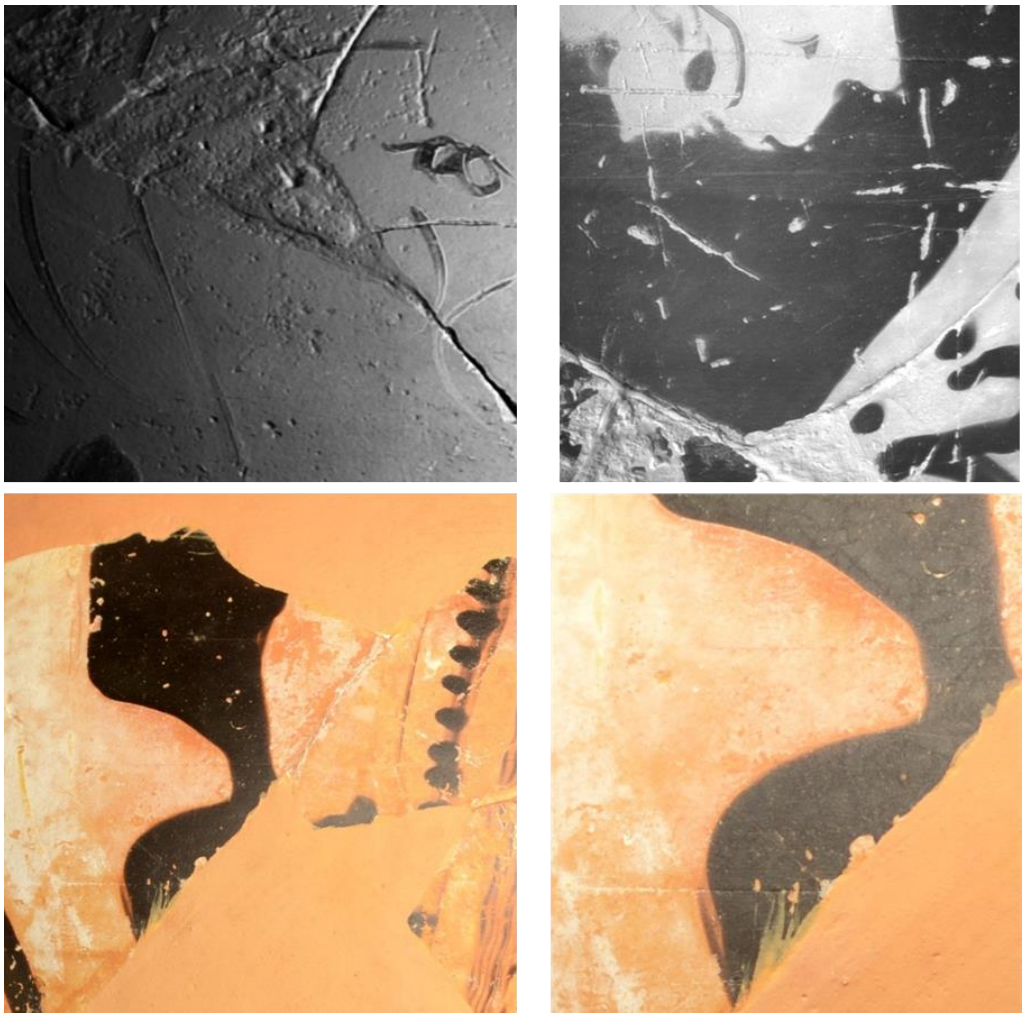


Figure 192: Red figure pelikes. Detail revealing surface topography and damage (Image author's own).

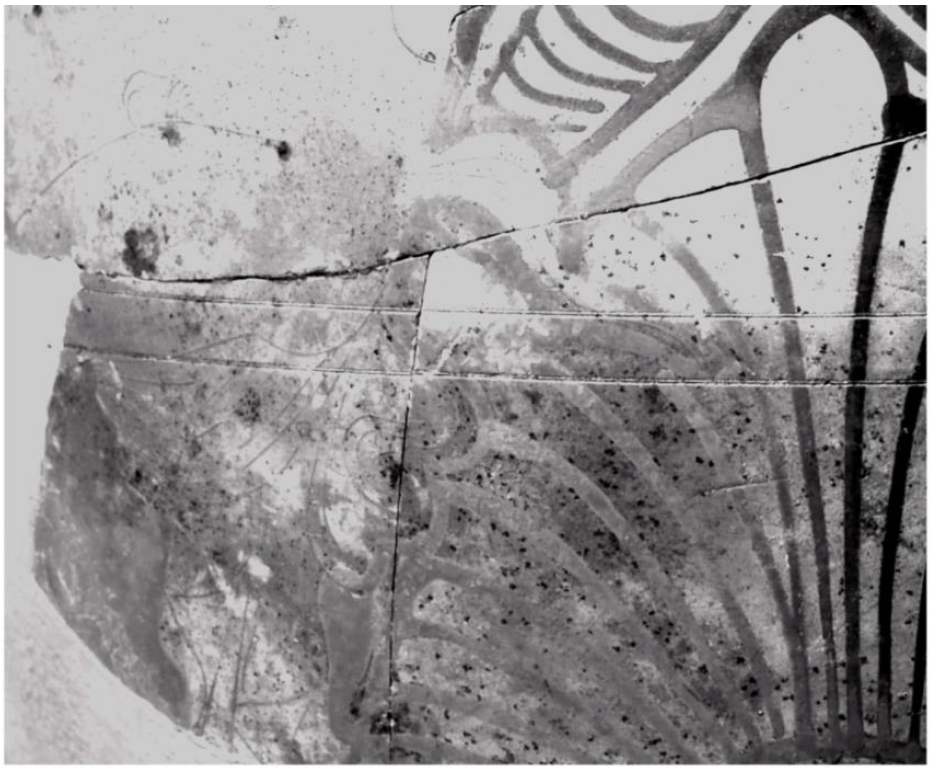


Figure 193: Red figure pelike H2. Detail, RTI visualization emphasizing incisions developed during construction possible from the ceramic wheel and revealing the preparatory drawing (Image author's own).

IR imaging proved to be a useful contribution in the examination of red-figure vases and a pseudo Cypriote amphora (Figure 194). The painted pattern of the amphora is emphasized and the leaves are differentiated from the background. The black and brown parallel lines appear more vivid, while in contrast the reddish and the whitish ones fade out. IR imaging provides an alternative view of the artefact, full of information, which can assist investigations of manufacturing technology, including materials and techniques, as well as condition reporting. In the IR image the deposition and saline encrustations, as well as the white colour appear eliminated, resulting in an enhanced visualization.

Figure 194: Pseudo-Cypriote Amphora. Height 0.281 m. Digital image (left), desaturated image (middle) and IR image (right) (Image author's own).

RTI provides an enhanced view of the artefacts under examination, which was significantly improved by the implementation of IR-RTI. Restored areas are also highlighted, providing evidence for previous repairs. While these characteristics appear partly hidden and obscured under visible light, they are emphasised in IR-RTI. As shown in Figure 195, the restored area is not discernible in digital image. In the normal RTI visualization it is visible and in the IR-RTI rendering the modern addition is clearly differentiated. The relief lines were highlighted, providing an enhanced view of the preparatory drawing, as well as the three dimensionality of the painted pattern. Considering that they were used to outline figure and details, IR-RTI views of the painted scene are particularly informative (Figure 196). Hence, IR-RTI provides the opportunity not only for enhanced condition reporting and documentation, but also examination of painting techniques and stylistic comparison of artefacts.

Figure 195: Detail, red figure pelike H2. Digital image (left) and RTI visualization (middle) and IR-RTI visualization (right) (Image author's own).

Figure 196: Detail, red figure pelike H2. Digital image (left) and RTI visualization (middle) and IR-RTI visualization (right) (Image author's own).

RTI visualization of the gnathian skyphos enabled detailed examination of the surface properties[33]. In the area of the handle the tiny lines reveal the pressure applied by the person who crafted for the skyphos when they attached the handle (Figure 197) and in the area of the body marks of the ceramic wheel are

[33] See Digital Library, folder section5.3, files USOU-UK_CER_GNb_VIS_MA-H.rti and USOU-UK_CER_GNa_VIS_MA-H.rti

observable (Figure 198). The infrared image of a detail from the skyphos demonstrates a differentiation in the response of the black glaze in the infrared radiation as a result of its poor state of preservation. Comparisons of the normal maps reveals the enhanced visualization of low relief detail, particularly in the lower area of the body, as well as the clearer representation of the wheel marks covered by encrustations in the upper area of the body (Figure 199)[34].

Figure 197: Gnathian skyphos, details, RTI visualization emphasizing fingerprints in the areas of the handle (Image author's own).

Figure 198: Gnathian skyphos, details, RTI visualization revealing marks possibly created by the ceramic wheel (Image author's own).

[34] See Digital Library, folder section5.3, file USOU-UK_CER_GNa_IR-850_MA-H.rti

Figure 199: Gnathian skyphos, comparison of digital images (left) and normal maps (right) in visible (top) and infrared spectral area (below) (Image author's own).

The ultraviolet induced visible fluorescence image reveals the remains of conservation materials on the surface of the ceramic skyphos and the previous repairs, because of the visible fluorescence emission of common adhesives used (Figure 200). It is known that in static UV induced visible fluorescence imaging the axial positioning of the radiation source, as well as moving the handheld radiation units around, are actions usually undertaken to facilitate improved documentation of objects and better perception of features revealed. The UV induced visible fluorescence RTI enables the user to virtually move the radiation source around the object leading to numerous different visualizations (Figures 201-203)[35]. In that way the conservator can reach a better understanding about the morphology of the previous repairs. Furthermore, by applying different rendering modes (see section 3.2.1.3.1 for a discussion on rendering modes), these features are emphasized.

Figure 200: Gnathian skyphos, detail, UV induced visible fluorescence (Image author's own).

[35] See Digital Library, folder section5.3, files USOU-UK_CER_GNa_UVF_MA-H.rti and USOU-UK_CER_GNb_UVF_MA-H.rti

Figure 201: Gnathian skyphos, UV induced visible fluorescence (Image author's own).

Figure 202: Gnathian skyphos, UV induced visible fluorescence normal map (Image author's own).

Figure 203: Gnathian skyphos, Ultraviolet induced visible fluorescence RTI visualizations in specular enhancement rendering mode (Image author's own).

Reflected UV-RTI offers the opportunity for enhanced examination of subtle surface variations. In the case of the skyphos, these variations are the remains of the conservation materials, the differentiations of the glaze due to its poor preservation and the salts' efflorescence. The UV-RTI provided in a single file a combination of axial and UV imaging (Figure 204)[36]. It is notable that the axial positioning of radiation sources in reflected UV imaging is *'advantageous'* and is proposed for recording of scratches and smudges (Warda *et al*., 2011, p.161). By applying the specular enhancement rendering mode and additional setting of the parameters the findings appear emphasised (Figure 205). The normal maps produced are complete representations of the surface topography of the surface in the ultraviolet region (Figure 206).

Figure 204: Gnathian skyphos, UV Reflected RTI visualization (Image author's own).

[36] See Digital Library, folder section5.3, file USOU-UK_CER_GNb_UVR_MA-H.rti

Figure 205: Gnathian skyphos, RTI visualizations in specular enhancement rendering mode, comparison of visible, infrared at 950nm, ultraviolet induced visible fluorescence and reflected ultraviolet (clockwise from top left) (Image author's own).

Figure 206: Gnathian skyphos, Normal maps, comparison of visible, infrared at 950nm, ultraviolet induced visible fluorescence and reflected ultraviolet (clockwise from top left) (Image author's own).

In the Faenza maiolica ceramic sherd the most interesting feature revealed from the RTI visualization was the surface anomaly-curvature, which may be associated to the lack of attachment of the glaze to the body as well as the three dimensionality of the low relief detail of the painted designs (Figure 207). Also, the network of cracks of the glaze, and the tiny blisters, were not visible in the digital images but appeared emphasized in the RTI renderings (Figure 208)[37]. The enhanced visualization and the perception of three dimensionality of the cracks pattern introduced by RTI can assist the study of the history of the object. For example, careful observation of the cracks' morphology reveals that their edges are straight, and by extension indicates the well-known phenomenon of crazing of glazes, which has been discussed extensively in the conservation literature. If the cracks had formed a different pattern with rounded edges, they would have been associated with cracking before the setting of the glaze. RTI visualization of the sherds covered with soil and deposits emphasized the painted pattern which was hardly visible in the digital images (Figure 209). In detail images the surface anomalies, the scratches, the surface topography of the deposits and the rough, porous ceramic texture in the areas where the glaze was missing can be observed (Figure 210).

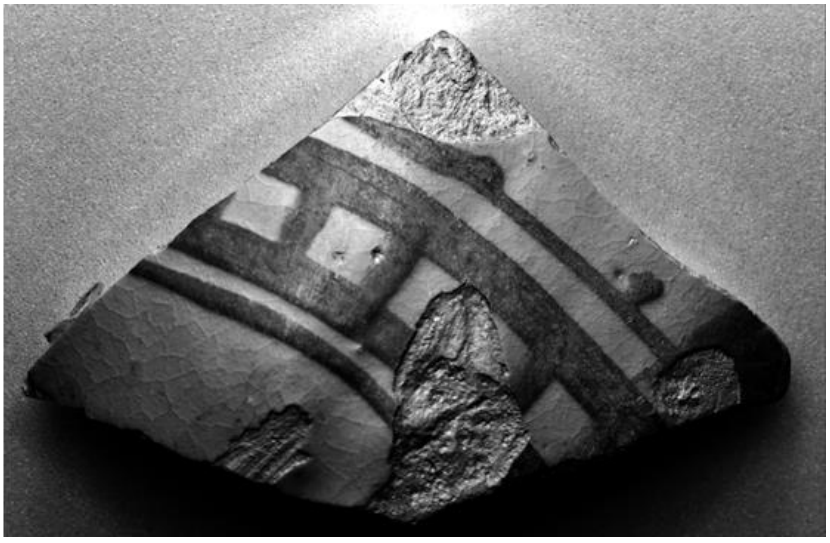


Figure 207: Faenza maiolica ceramic shred, RTI visualizations in specular enhancement rendering mode (top) and normal maps (below) (Image author's own).

[37] See Digital Library, folder section5.3, file SCC-UK_CER_366-1-VIS-MA-H.rti

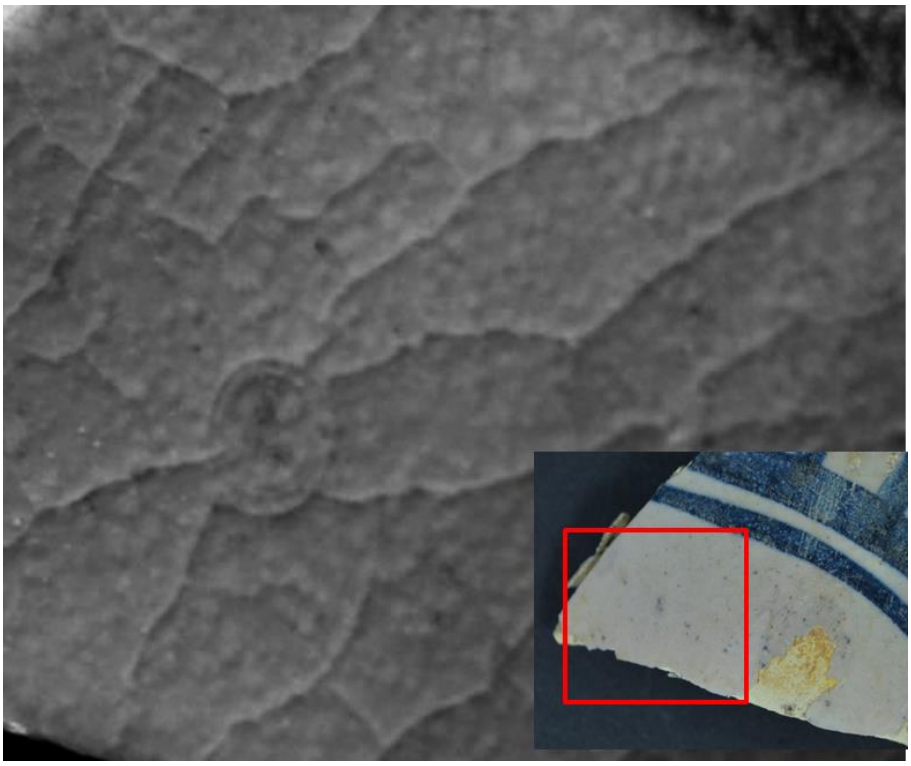


Figure 208: Detail of Faenza maiolica ceramic shred, RTI visualization in specular enhancement rendering mode (Image author's own).

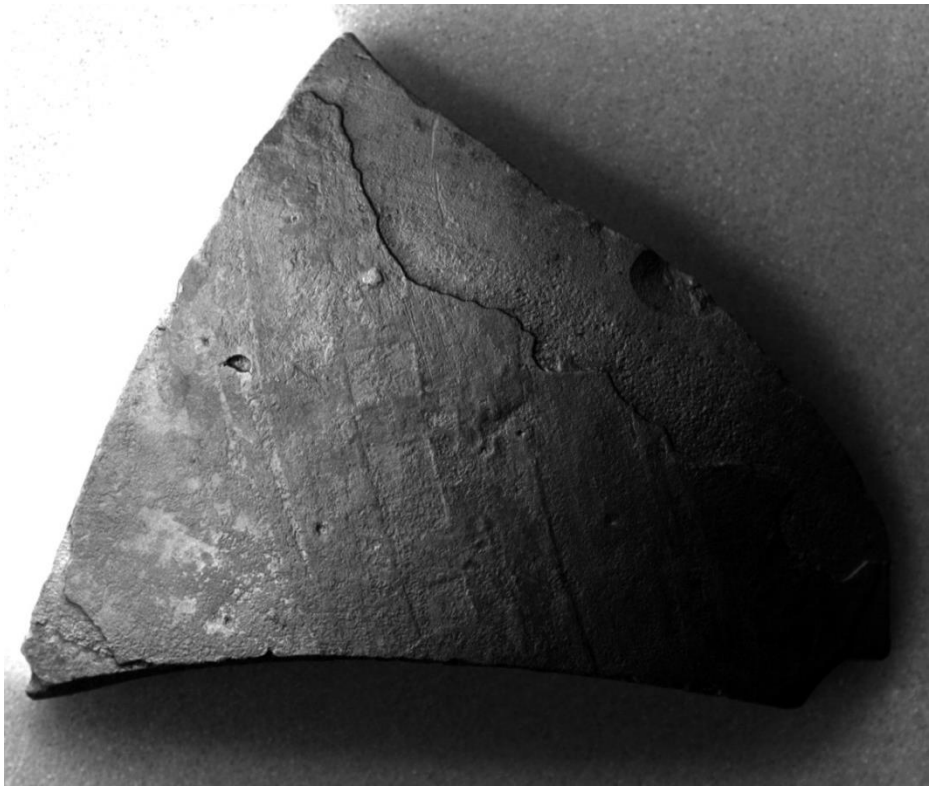


Figure 209: Tin glazed ceramic shred, RTI visualization in specular enhancement rendering mode (Image author's own).

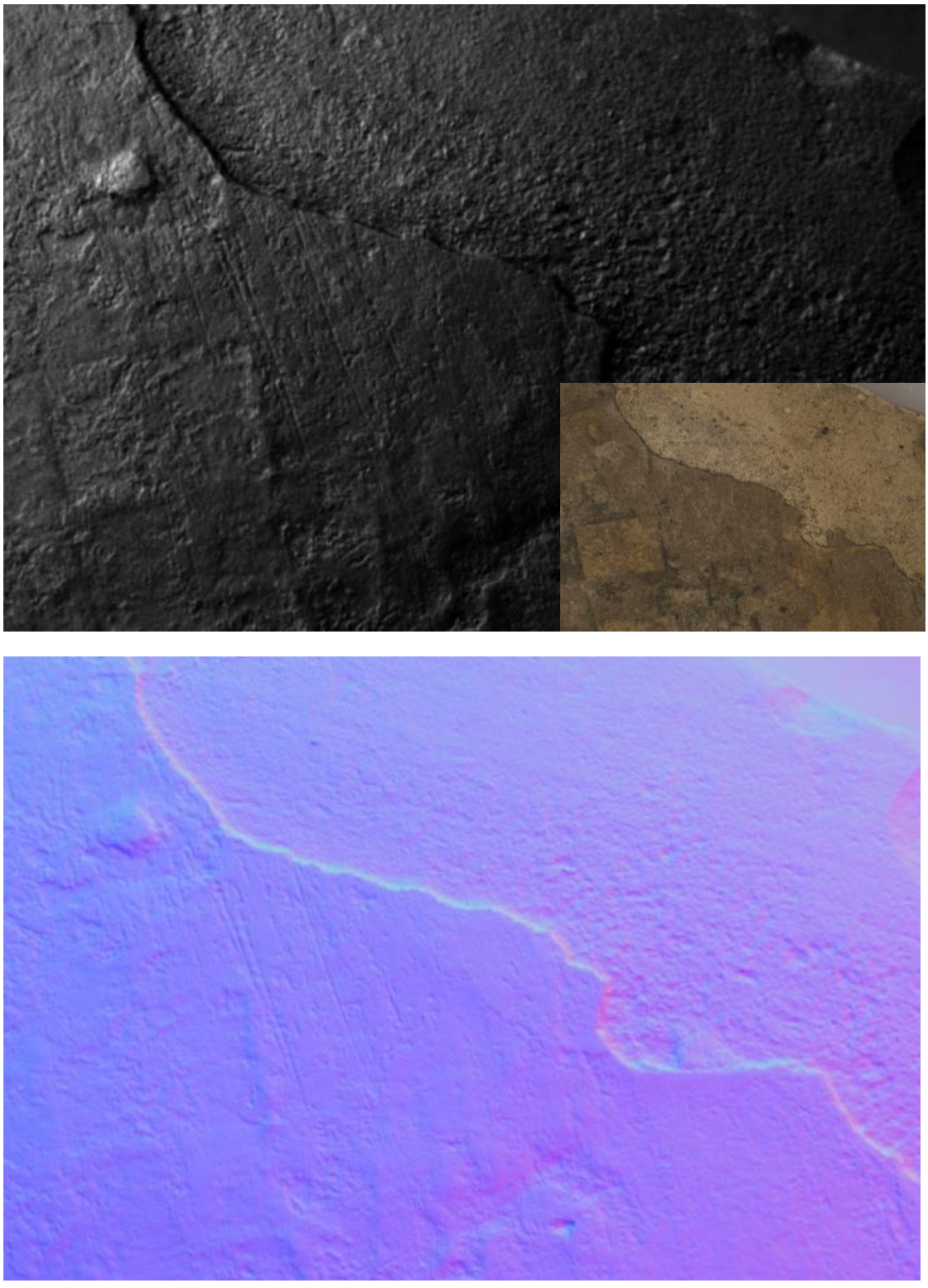


Figure 210: Faenza maiolica ceramic shred, detail, RTI visualization in specular enhancement rendering mode (top) and normal map (below) (Image author's own).

Infrared imaging of the ceramic sherd covered with superficial dirt and deposits reveals the painted design. In case of the clean sherd the preparatory drawing and the application of colour can be examined. In the presence of different colours, their varying response can assist in materials differentiation and characterization (Figure 211). Infrared RTI visualizations reveal the three dimensional characteristics of the paint layer, while the layer of depositions appear significantly eliminated due to the penetration ability of infrared irradiation, as demonstrated by the comparison of RTI renderings between the visible and IR spectral area from the same light parameters (Figure 212). Infrared radiation penetrates the paint layer and the cracking of the substrate is revealed (Figures 213-214)[38]. A complete RTI visualization includes captures in the visible, infrared and ultraviolet spectral region. Different visualizations emphasise a range of features, as shown in the example of a Faenza maiolica fragment in Table 12.

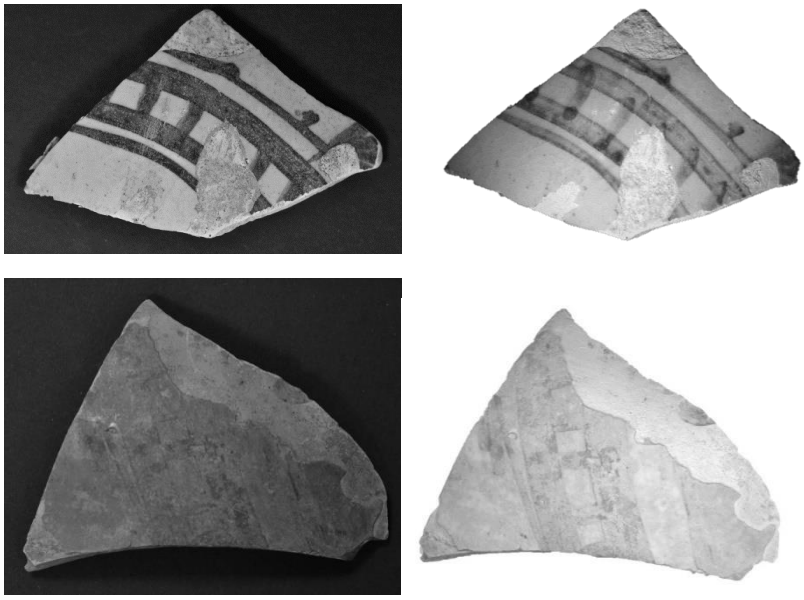


Figure 211: Faenza maiolica shreds, comparison of visible desaturated (left) and and IR images (right) (Image author's own).

[38] See Digital Library, folder section5.3, file SCC-UK_CER_366-1-IR-850-MA-H.rti

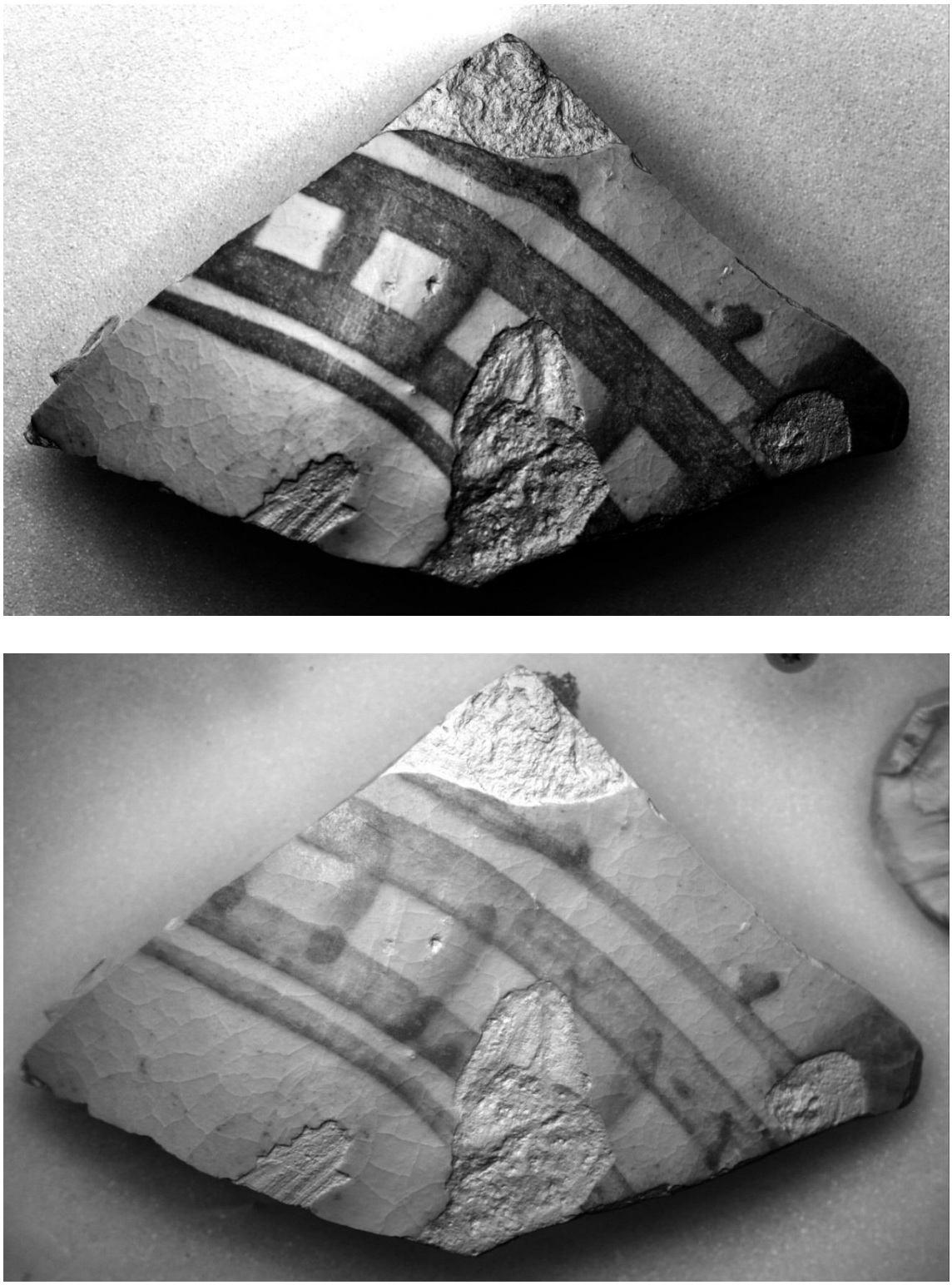


Figure 212: Faenza maiolica shreds. Comparison of visible (top) and IR-RTI visualization (below) (Image author's own).

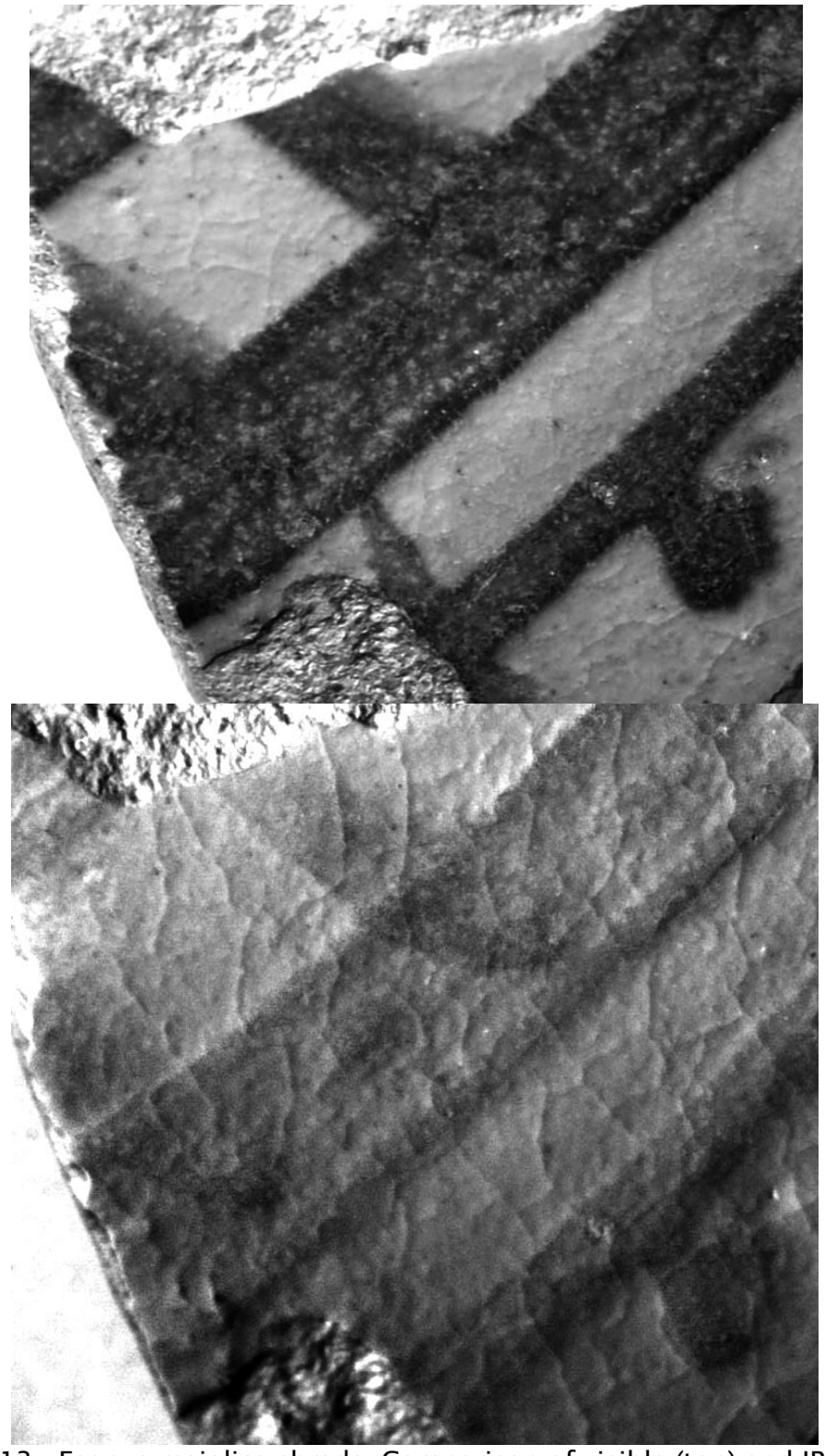


Figure 213: Faenza maiolica shreds. Comparison of visible (top) and IR-RTI visualization (below) (Image author's own).

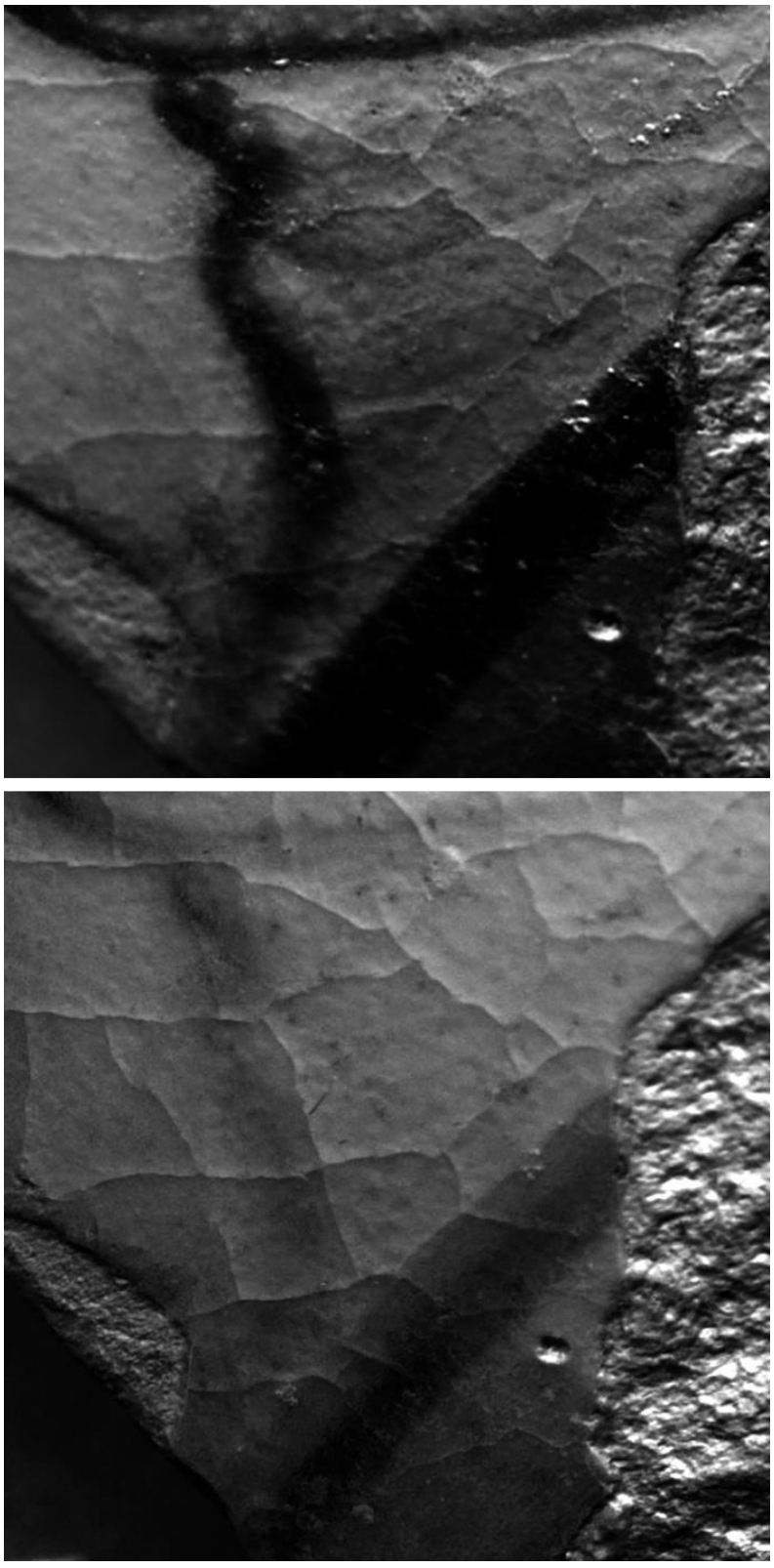
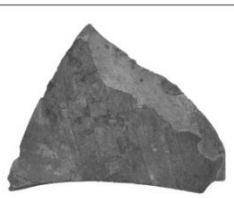
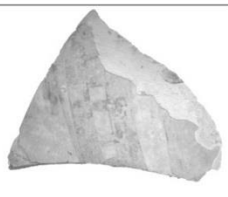
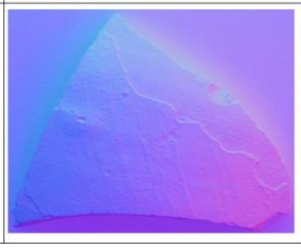
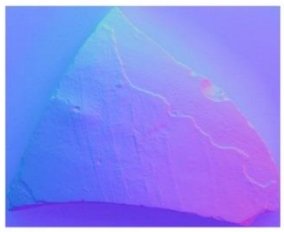
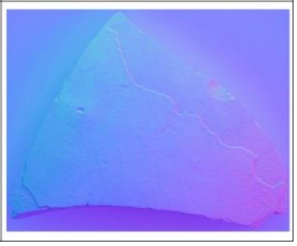


Figure 214: Faenza maiolica shreds. Comparison of visible (top) and IR-RTI visualization (below) (Image author's own).

Table 12: Fragment from Faenza maiolica jug 367. Complete RTI visualization.

	visible	infrared 950nm	ultraviolet
digital images			
RTI visualizations in default rendering mode			
RTI visualizations in specular enhancement rendering mode			
normal maps			

Apart from vases and vessels other types of ceramics can be benefited by RTI visualization. A characteristic example is the group of gilded and/or painted ceramic roundels with the head of Athena Parthenos, discovered in Derveni Tomb B. Because of the small size of the roundels (diameter 0.022m) macro and microscopic RTI technique was used, which enable documentation of craquelure, flaking and loss of red colour layer, flaking, loss and cracking of gold decoration, salt efflorescence and depositions and examination of the facial features (Figure 215-218)[39].

[39] See Digital Library, folder section5.3, files AMTH_GR_CER_A99a_VIS-MI-H.rti, AMTH_GR_CER_A99b_VIS-MI-H.rti, AMTH_GR_CER_A99c_VIS-MI-H.rti, AMTH_GR_CER_A99d_VIS-MI-MD2.rti and AMTH_GR_CER_A99e_VIS-MI-MD1.rti

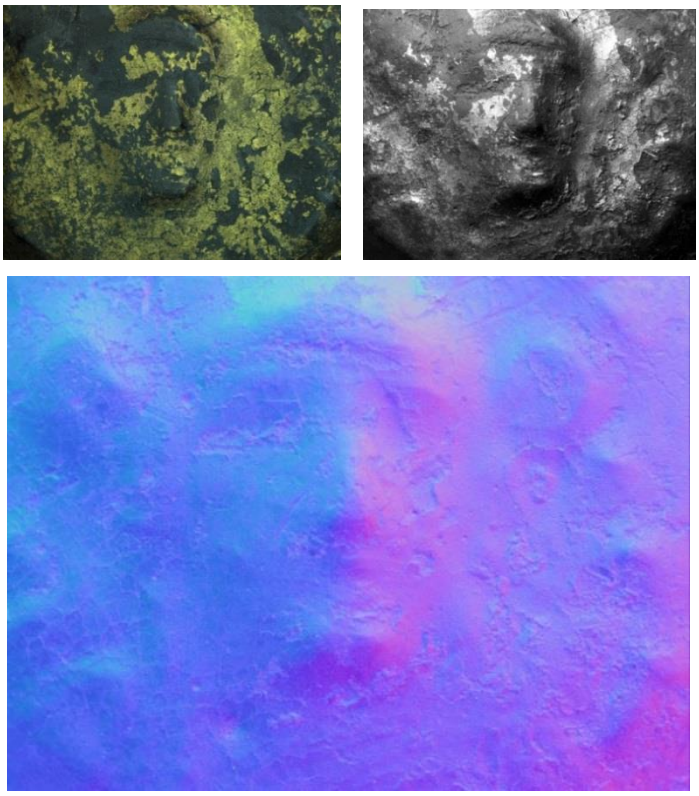


Figure 215: Gilded roundel, digital image (top left) and RTI visualizations (Image author's own).

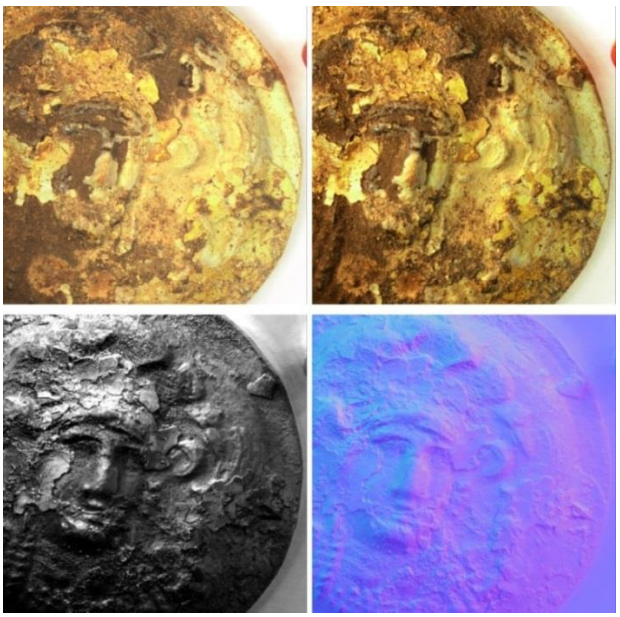


Figure 216: Gilded roundel, digital image (top left) and RTI visualizations (Image author's own).

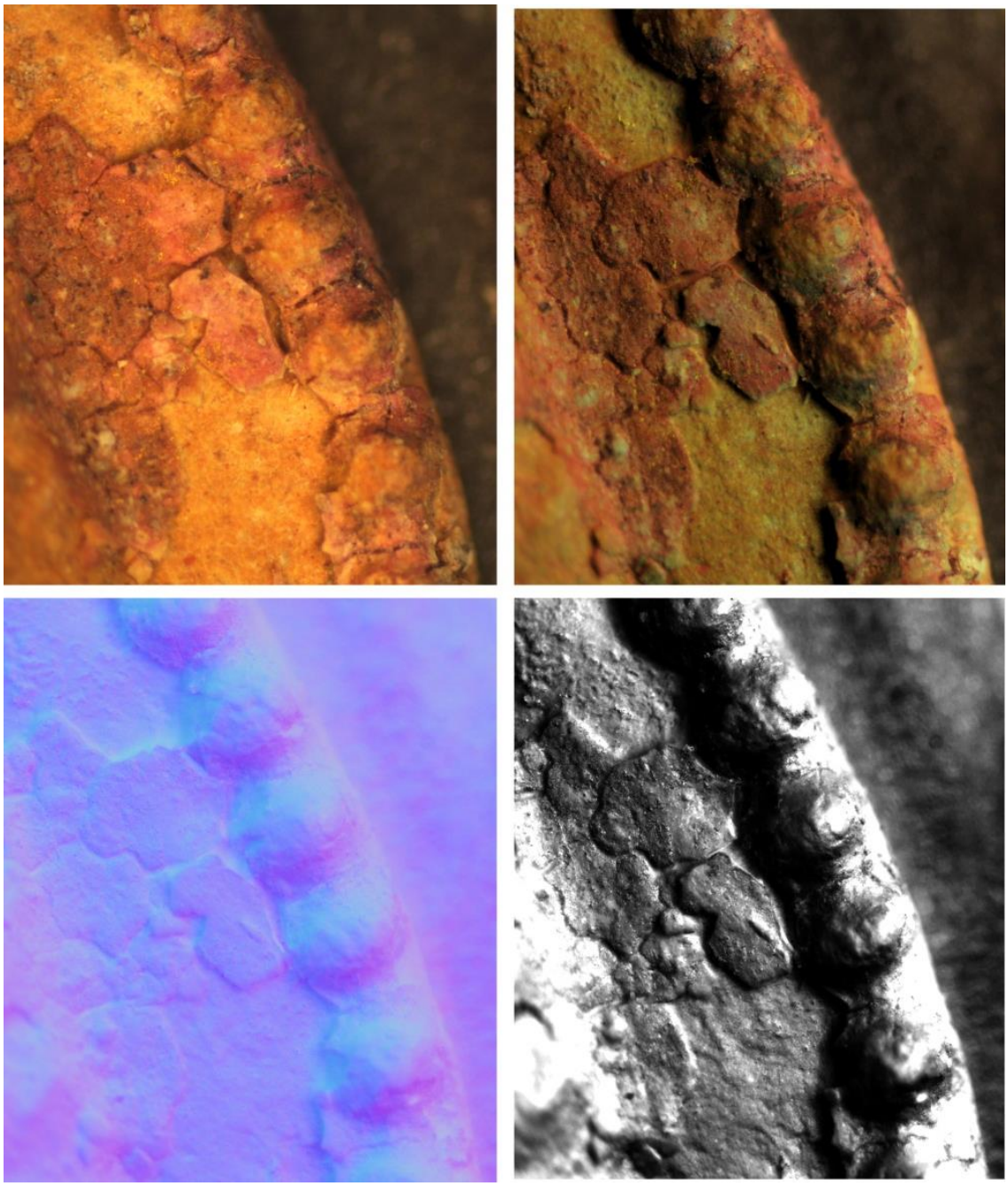


Figure 217: Gilded roundel, digital image (top left) and RTI visualizations (Image author's own).

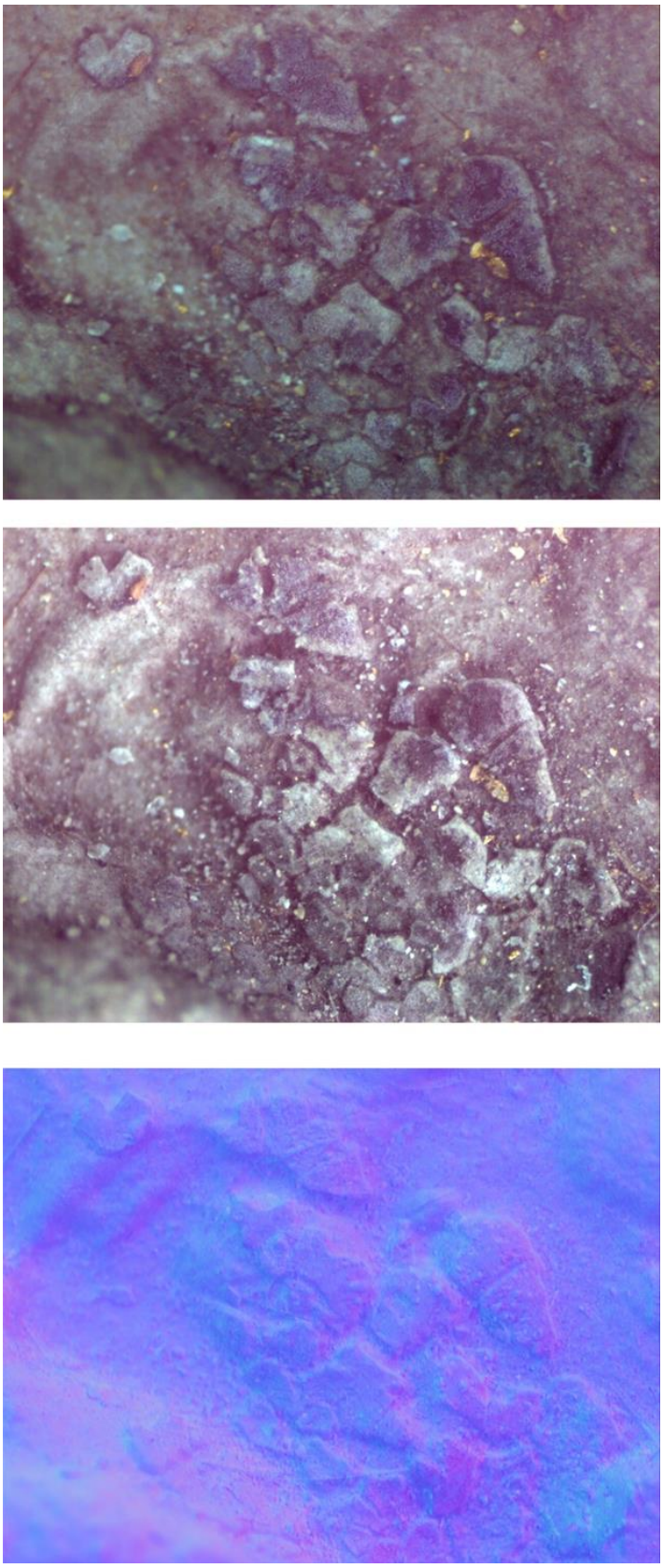


Figure 218: Gilded roundel, digital image (top) and RTI visualizations (below) (Image author's own).

5.3.2.2.5 Organics

RTI is a useful tool in case of organic excavated materials, which call for advanced non-contact documentation and examination due to their unstable nature. In wood fragments shrinkage, warping and cracking as well depositions can be observed. Also, the identification of the grain direction, significant information for the examination of wood, is possible through RTI (Figure 219). In leather artefacts[40] RTI enables examination of degradation effects, such as splits, tears, shrinkage, cracking, encrustation, depositions and interesting phenomena, such as mineralization[41] and delamination (Figures 220-223). Microscopic details can lead to the detection of use evidence. For example, loss of the original material of a belt/strap around the inner hole and diagonally to the peripheral diameter indicates alteration caused by friction (Figures 224-225). In skeletal material[42] RTI can locate and document physical damage and decoration, offering possibilities for enhanced examination. Losses of original material, pits and depositions can be documented. It can also assist revelation activities, emphasizing incised lines and remnants of colour decoration, while the discrimination between engravings and damage becomes easier (Figures 226-230).

Figure 219: Wood fragment part of a wreath. Digital image (left) and RTI visualizations (right) (Image author's own).

[40] See Digital Library, folder section5.3, files AMTH_GR_LEA_A21_VIS-MA-H.rti, AMTH_GR_LEA_A21_VIS-MI-MD1.rti and AMTH_GR_LEA_B114_VIS-MI-MD1.rti
[41] See Digital Library, folder section5.3, file AMTH_GR_COM_B114_VIS-MA-H.rti
[42] See Digital Library, folder section5.3, files AMTH_GR_IVO_E7_VIS-MA-H.rti, AMTH_GR_IVO_E8a_VIS-MI-MD1.rti and AMTH_GR_IVO_E8b_VIS-MI-MD1.rti

Figure 220: Leather fragment attached to a copper alloy ring (A114). Length 4cm. Digital image (top) and RTI visualizations of details (down) (Image author's own).

Figure 221: Leather fragment with textile imprints (B109). RTI visualization (Image author's own).

Figure 222: Burnt leather fragment with holes at serial arrangement for sewing (A21), RTI visualization (Image author's own).

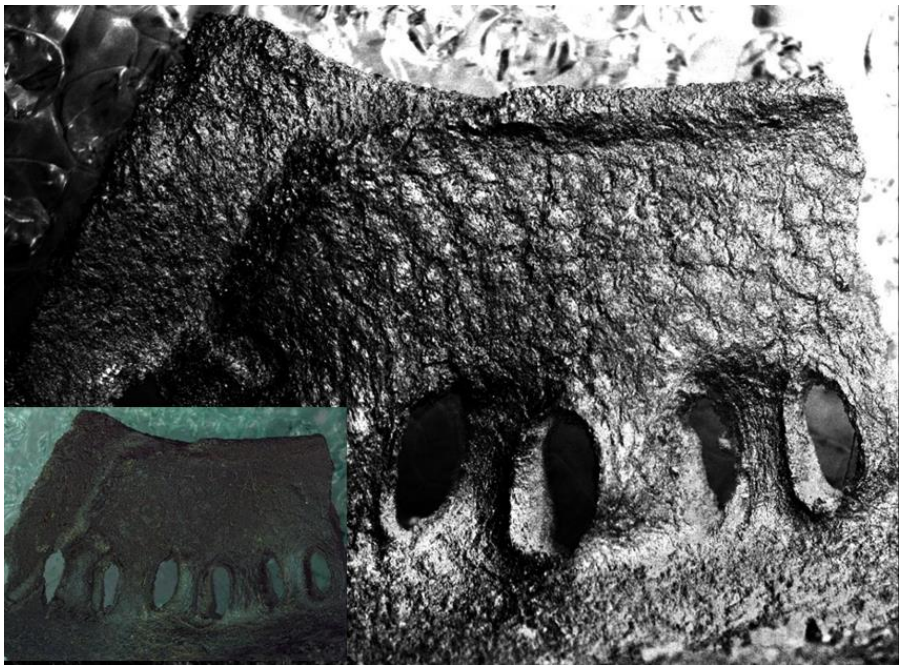


Figure 223: Burnt leather fragment with holes at serial arrangement for sewing (A21). RTI visualization (Image author's own).

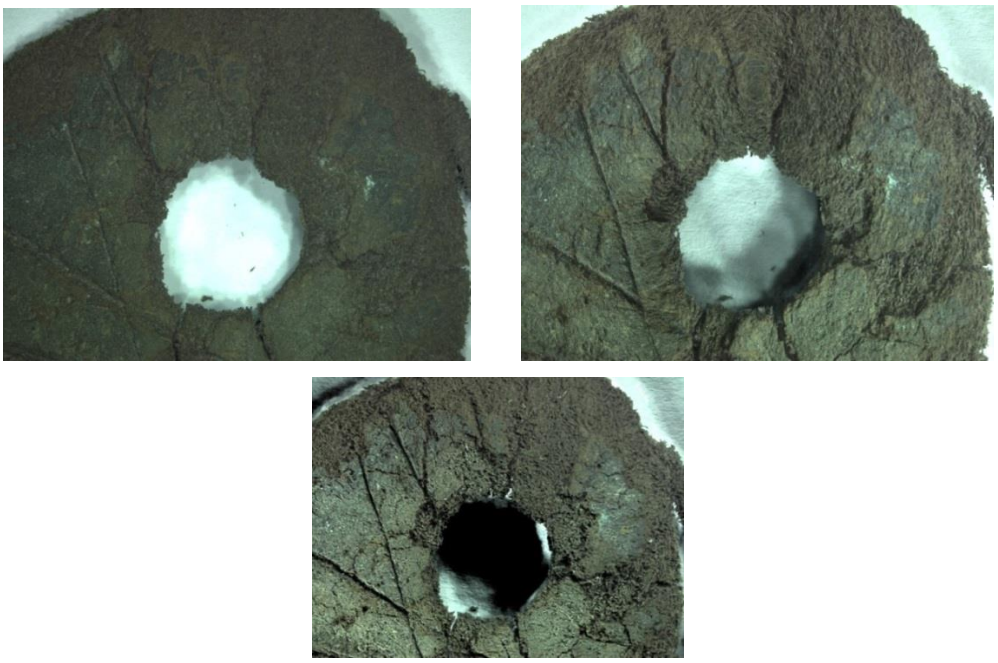


Figure 224: Leather fragment of a belt/strap. 1 cm. Digital image (top left) and RTI visualizations (top right, below) (Image author's own).

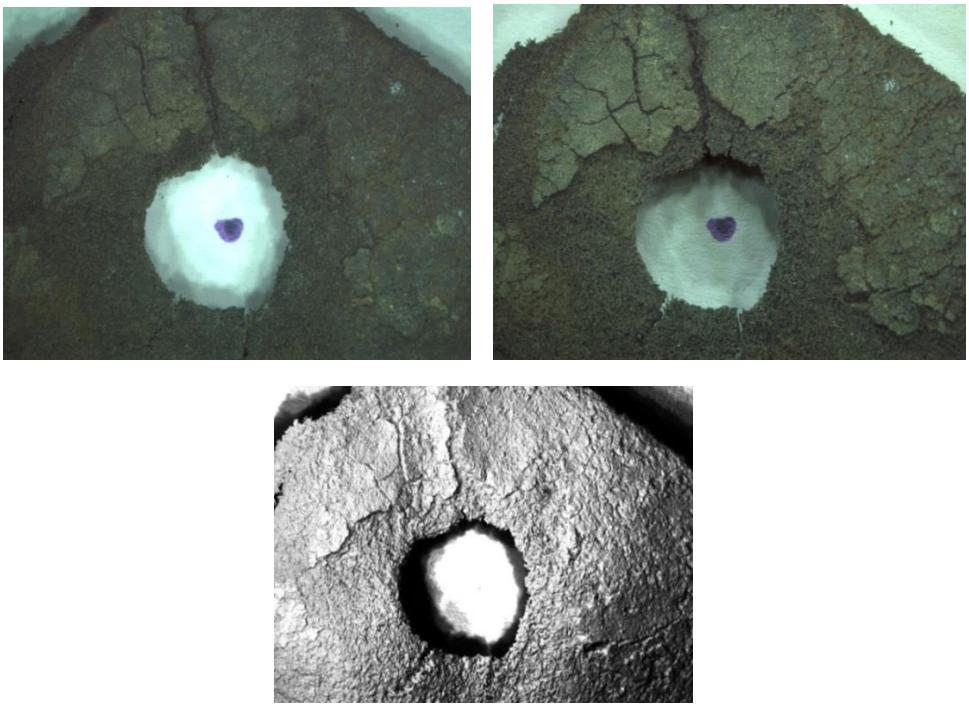


Figure 225: Leather fragment of a belt/strap. 1 cm. Digital image (top left) and RTI visualizations (top right, below) (Image author's own).

Figure 226: Incised ivory plaque fragment (E7a). Detail of Eros with remnants of colour decoration (blue and red). Digital images (top) and RTI visualizations of details (middle, down) (Image author's own).

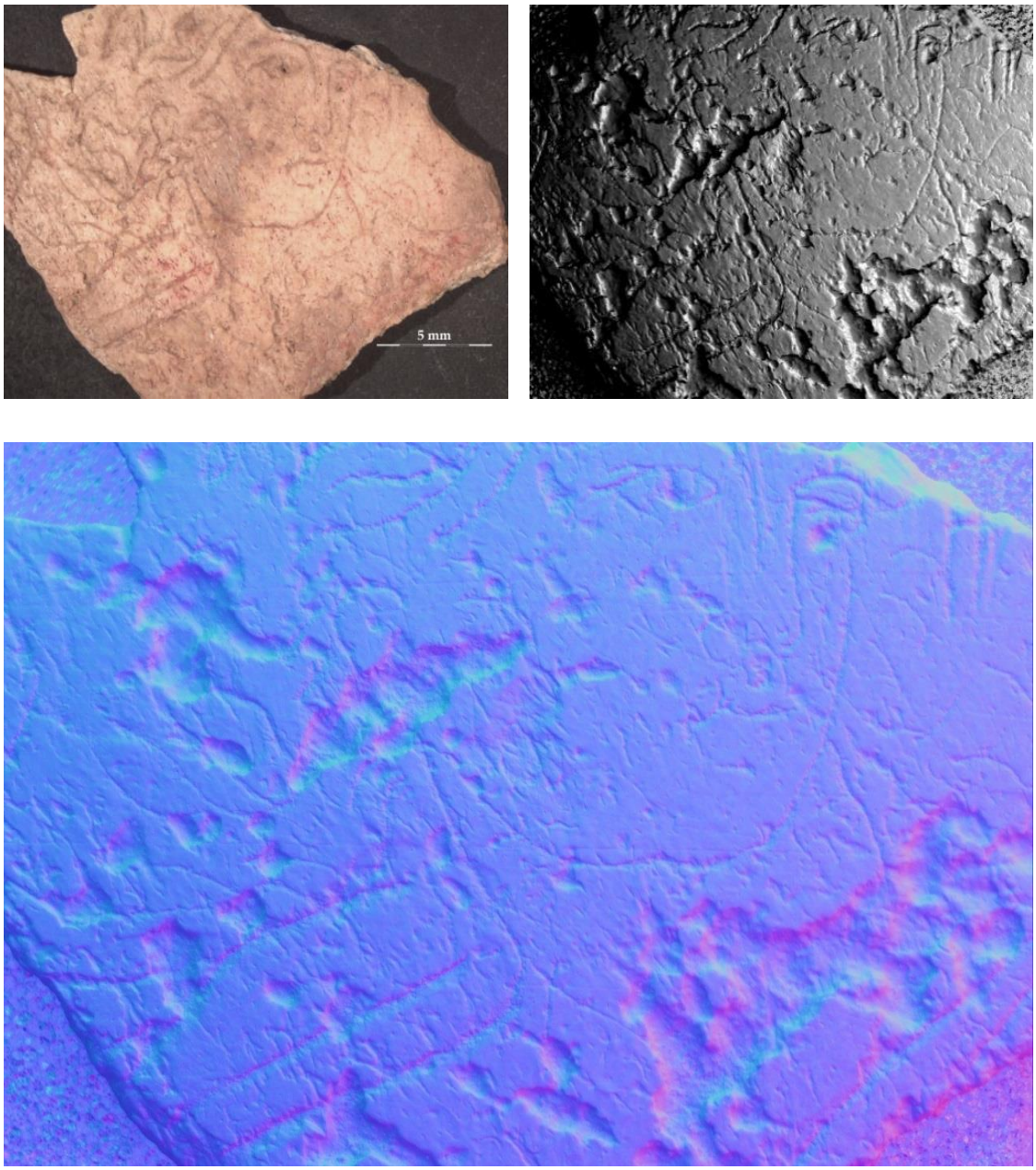


Figure 227: Incised ivory plaque, fragment (E8a). Detail of young male with remnants of red colour. Microscopic image of fragment 1.5 cm. (top left), RTI visualizations (top right) and normal map (below) (Image author's own).

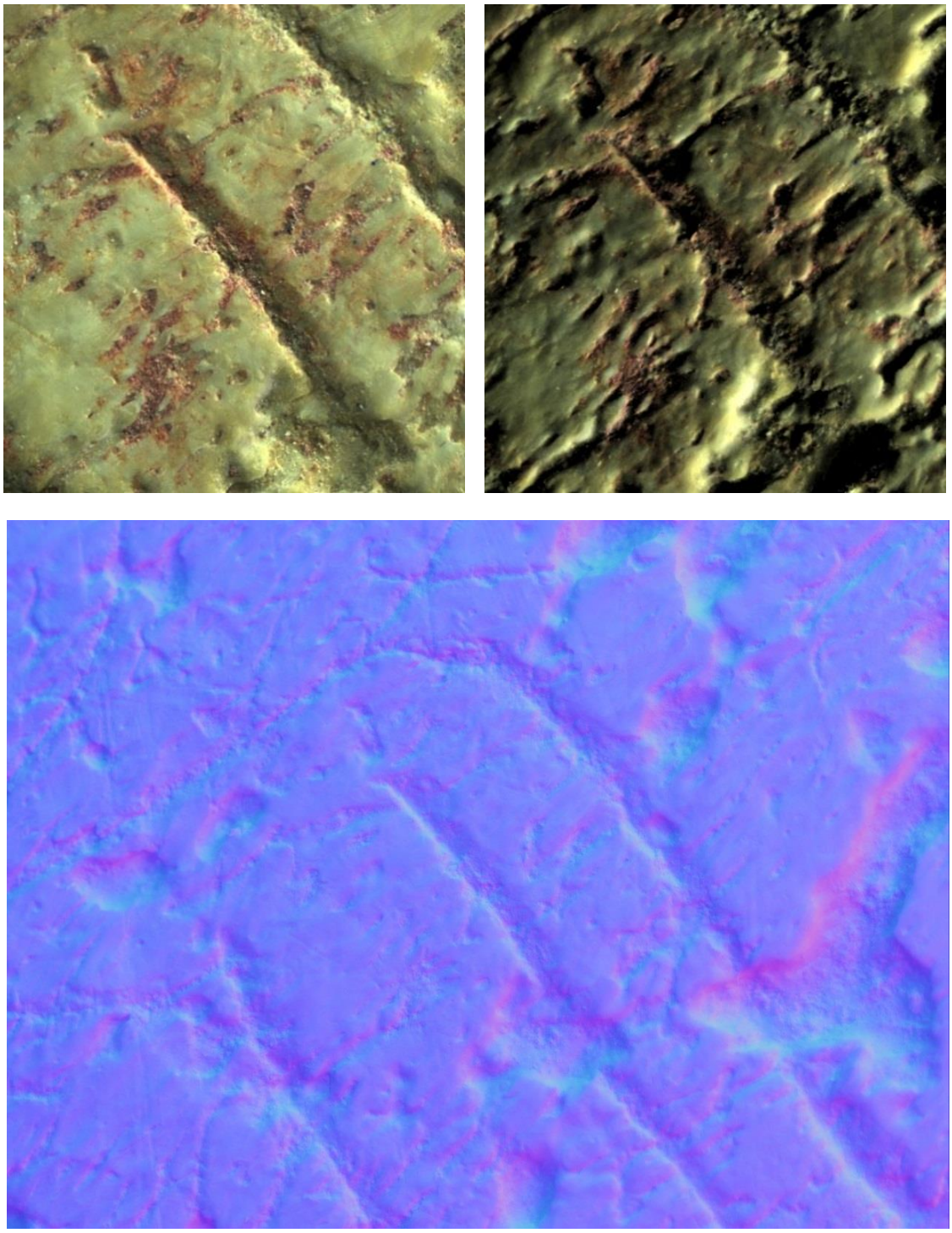


Figure 228: Incised ivory plaque, fragment (E8b). Detail of woman's clothing with remnants of red colour. Microscopic image of 1 cm (top left) RTI visualizations (top right) and normal map (below) (Image author’s own).

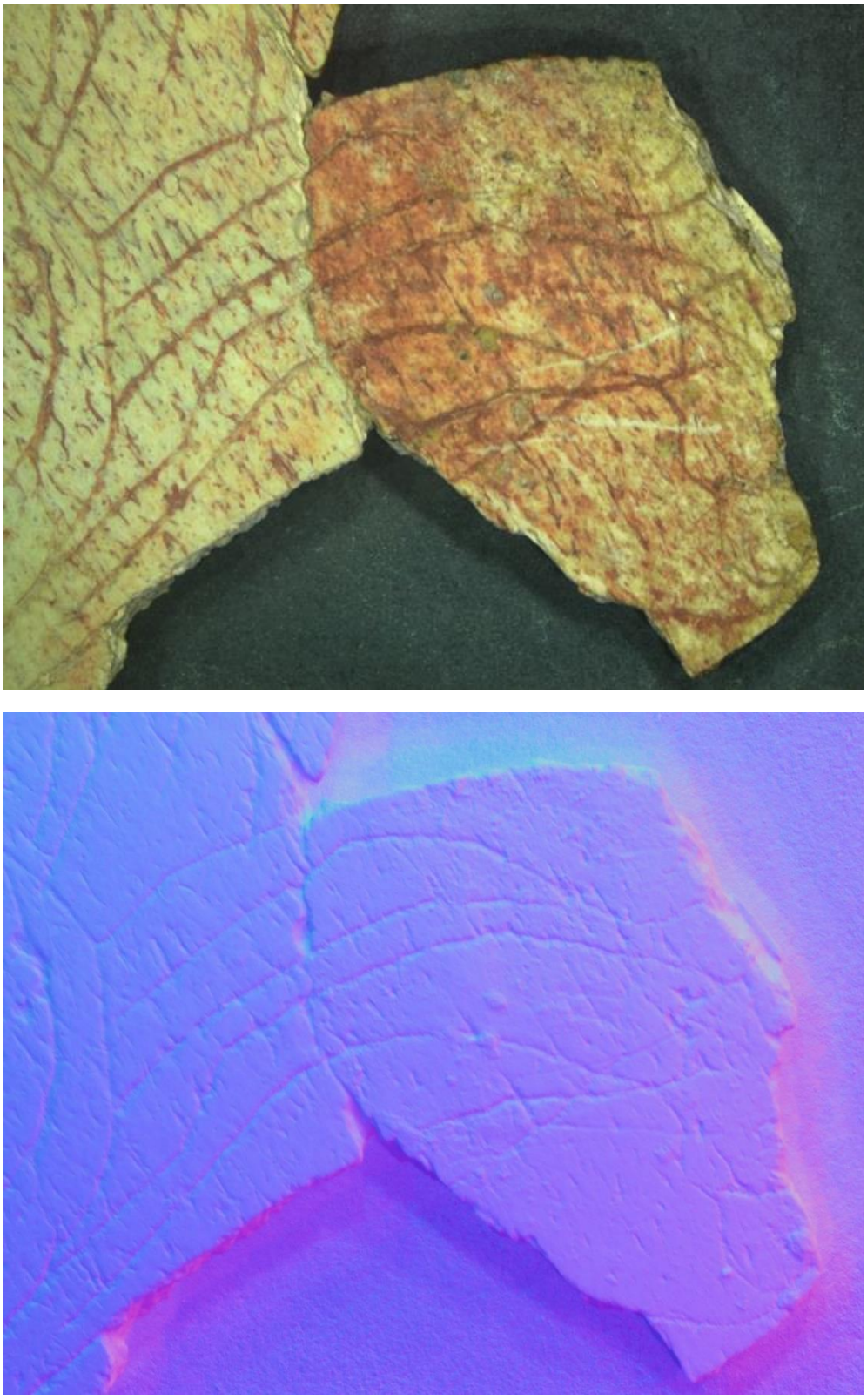
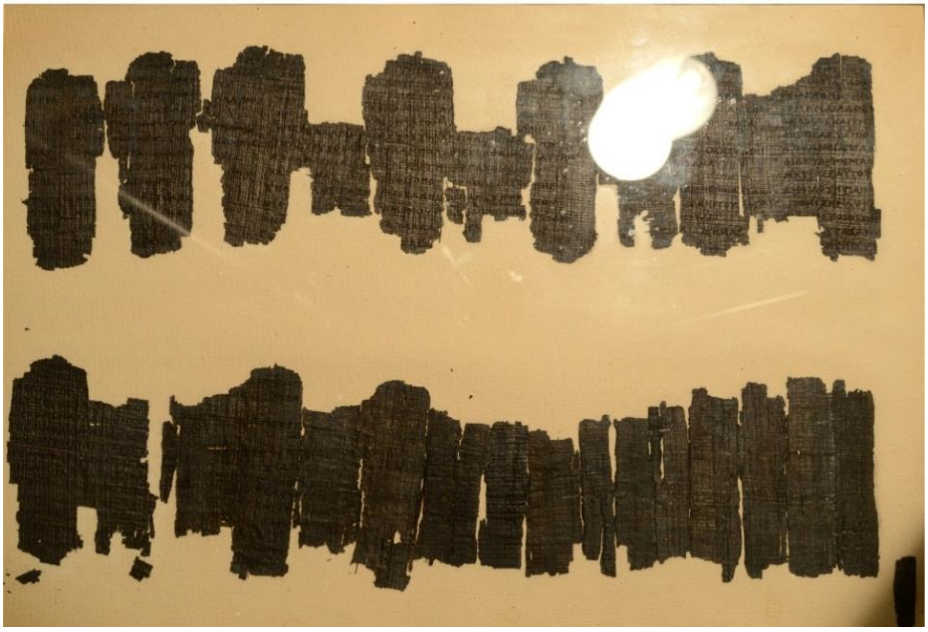


Figure 229: Incised ivory plaque, fragment (E8b). Microscopic image (top) and normal map (below) (Image author's own).

Figure 230: Bone handle of knife (0.24m). Digital image (top) and RTI visualizations of detail (down) (Image author's own).

Fragments of the Derveni papyrus roll, discovered carbonized in the remains of a funeral pyre, are preserved glass-mounted, sandwiched between two sheets of glass. One glass mount was captured with reflected and transmitted illumination and infrared radiation, resulting in a series of RTI files[43]. The recto (front side) was captured with visible reflected illumination and infrared radiation at 720nm, 850nm and 950nm. The verso (back side) was captured with reflected visible light and infrared radiation at 850nm, as well as with trans illumination and trans irradiation at 850nm. The initial hypothesis for the RTI visualization of the Derveni papyrus, based on previous experience in the field of reflectance transformation technologies, was that RTI would enhance the study of the papyrus, due to its ability to emphasize texture and colour. However, following the exact mainstream methodology as explained in the guide for H-RTI, data capture was not possible. The reflections of the flash on the glass mount resulted in unacceptable images (Figure 231). However, this phenomenon occurs only with wider angles, so the H-RTI procedure was applied but using only a subset of potential capture data, where the incident illumination angle was low.



[43] See Digital Library, folder section5.3, files AMTH_GR_PAP_VIS-H.rti, AMTH_GR_PAP_T-VIS-H.rti and AMTH_GR_PAP_IR-950-H.rti

Figure 231: The Derveni Papyrus fragments, digital image excluded from RTI dataset because of reflections of the flash on the mount (Image author's own).

The comparison between the digital images and the RTI visualization demonstrates that RTI visualization is an improved method for the study of ancient texts (Figure 232). It is a common practice for scholars to move the papyrus in their hands, in order to reveal the letters due to the different reflectance properties of the matte ink and the shiny papyrus background (Janko 2002). RTI offers the opportunity to perform this examination virtually avoiding any human-object interaction.

Figure 232: Detail of Derveni Papyrus fragment, comparison of digital image (left) and RTI visualization (right) (Image author's own).

Apart from the study of the texts, a complete visual analysis is possible via RTI, including examination of the manufacture techniques as well as determination of papyrus condition and conservation needs. As shown in Figure 233, RTI visualization emphasizes damage and alterations on the surface of the papyrus material, such as cracks, losses, flaking and distortions. In that sense RTI can be used as a tool, so as to monitor the extent of the on-going deterioration, and guide conservation treatment. Moreover, RTI can document areas in need of repair and twisted fibres, assisting the process of realignment in the correct position. Another advanced option for research provided by RTI is the examination of the papyrus fibres and the study of the criss-cross pattern (Figure 234). Comparative RTI analysis of papyrus fragments visualised in RTI form can help researchers reach conclusions regarding different papyrus

manufacture techniques. In addition, previous repairs such as joins can be documented (Figure 235). Considering that the vast majority of previous repairs are not documented, RTI can assist in understanding the papyrus's biography by revealing signs of treatments or operations executed in the past.

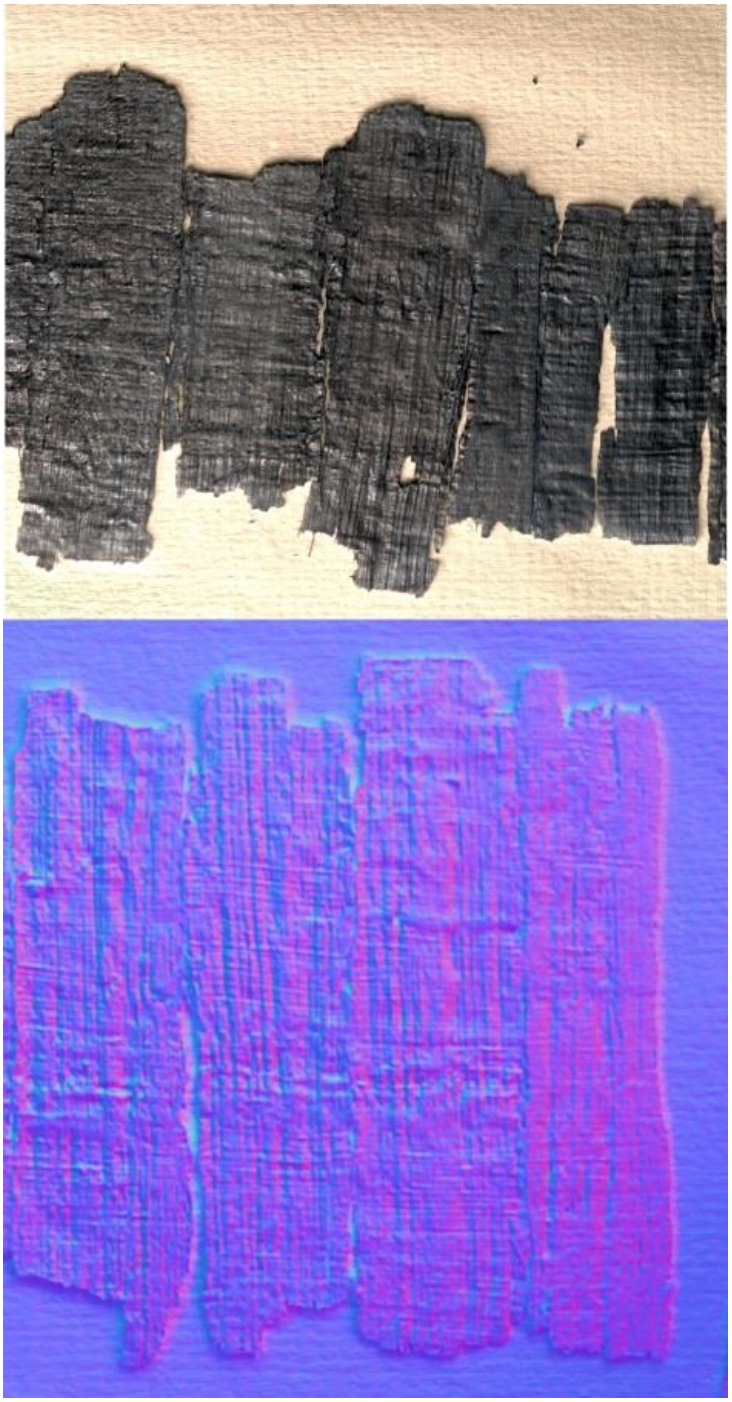


Figure 233: Detail of Derveni Papyrus fragment, RTI visualizations emphasizing damage and alterations of the papyrus material (Image author's own).

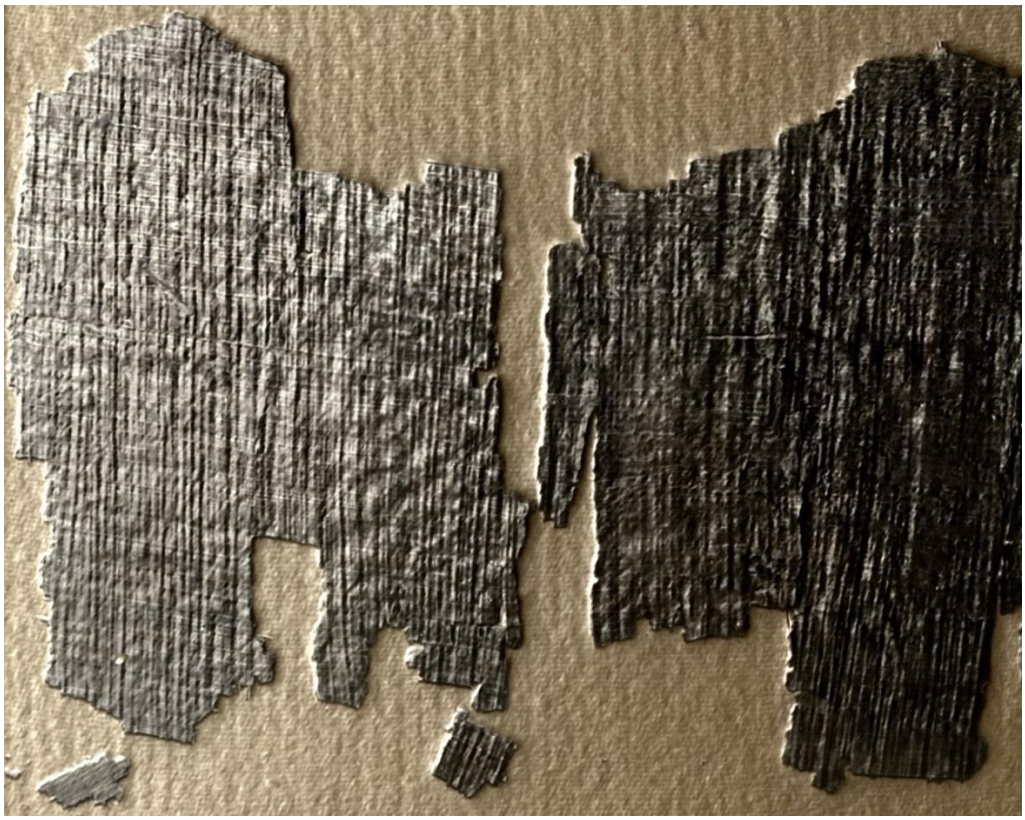


Figure 234: Detail of Derveni Papyrus fragment, RTI visualization emphasizing criss-cross papyrus pattern (Image author's own).

Figure 235: Detail of Derveni Papyrus fragment, RTI visualization emphasizing the joins of previous conservation treatment (Image author's own).

Virtual relighting of the glass mounted DP fragment emphasizes different features. For example, using the specular enhancement rendering (Malzbender *et al*., 2004) at the edges of RTI space emphasizes the texture of the papyrus, the criss-cross pattern and the irregularities introduced due to degradation and conservation treatment (Figure 236). The writings appear clearer in sharpening or in specular enhancement rendering mode at less extreme angles with maximum specularity and minimum diffuse colour and highlight size (Figure 237). The multi-light rendering mode successfully underlines both texture and writing (Figure 238).

Figure 236: Detail of Derveni Papyrus fragment, RTI visualizations in specular enhancement rendering mode at the edges of RTI space (Image author's own).

Figure 237: Detail of Derveni Papyrus fragment, RTI visualizations in specular enhancement rendering mode at less extreme angles with maximum specularity and minimum diffuse colour (Image author's own).

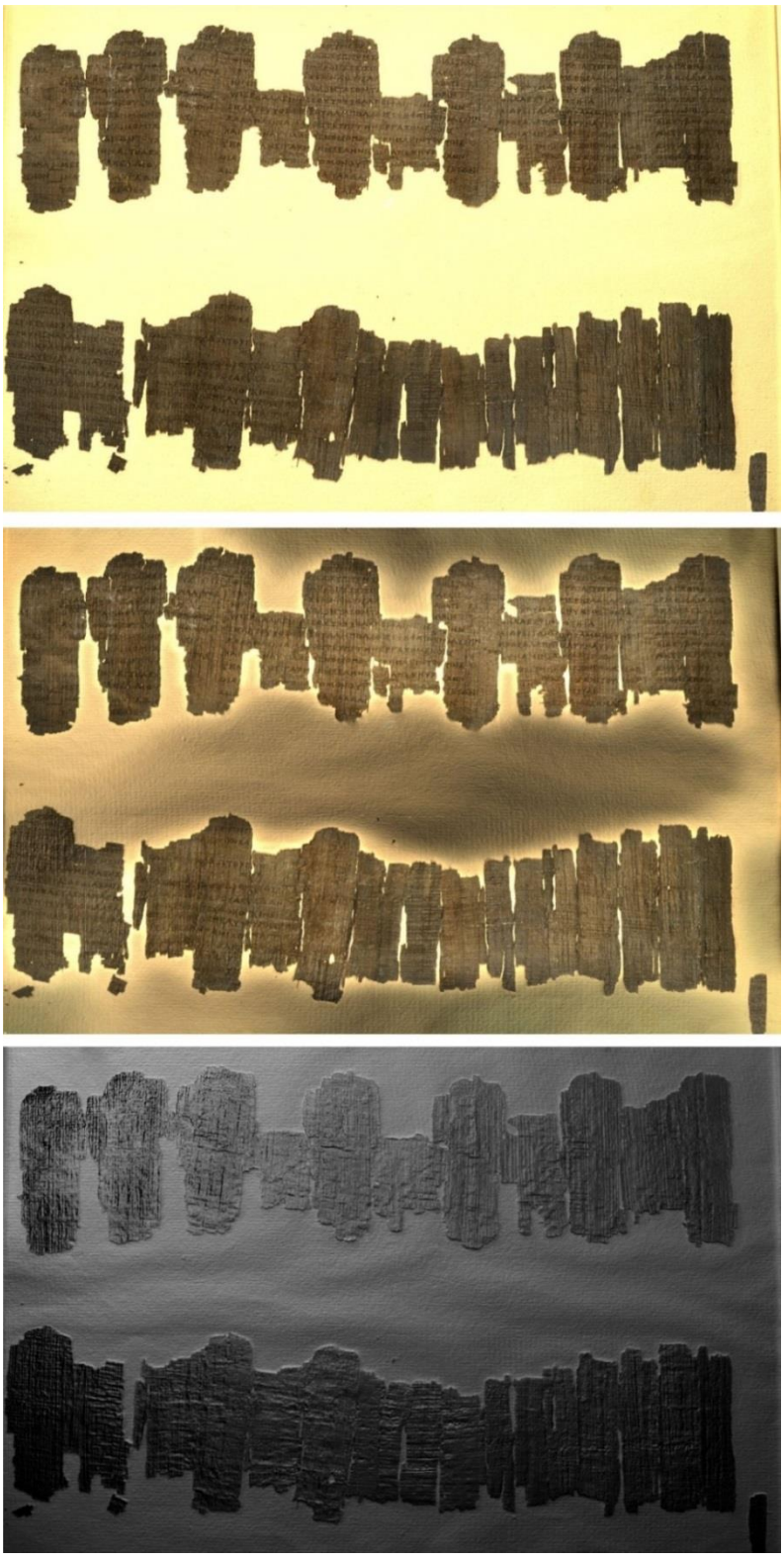


Figure 238: The Derveni Papyrus fragments, comparison between RTI visualizations in image unsharp masking (top), multi-light (middle) and specular enhancement rendering mode (below) (Image author's own).

In the Derveni Papyrus RTI case study the IR-RTI emphasises the three dimensional characteristics of the object and consequently assists the Derveni papyrus examination, while the texts can be examined more efficiently. The enhanced view of the papyrus fragment under examination, provided by RTI and IR imaging, was significantly improved by the implementation of IR-RTI. The legibility of the writings is particularly enhanced as shown in Figures 239 and 240. Also, the three dimensionality of the papyrus is emphasized. Via IR-RTI, the distortion of both the papyrus and its backing on the verso can be documented and examined (Figure 241). This distortion, caused probably by the backing material, should be monitored so as to avoid further fractures of the papyrus fragment.

Trans illumination RTI provides an enhanced RTI visualization, complementary to reflected RTI. It proved particularly useful for the visualization of the back side of the papyrus fragments which was covered by the backing material (Figure 242). The features highlighted were the fractures and incorrectly aligned fibres, as well as fibre structure and joins between sheets of papyrus.

Figure 239: Details of Derveni Papyrus fragment, RTI visualizations, comparison of renderings in visible (left) and IR spectral area (right) (Image author's own).

Figure 240: Details of Derveni Papyrus fragment, RTI visualizations, comparison of renderings in visible (left) and IR spectral area (right) (Image author's own).

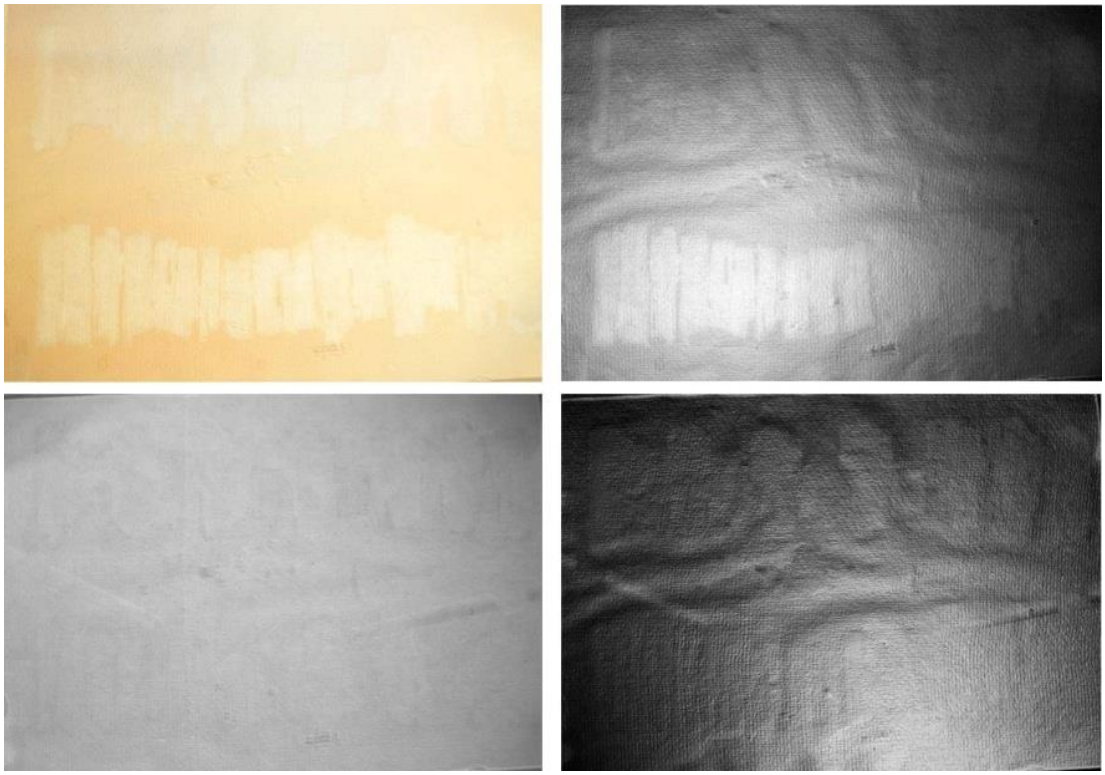


Figure 241: Derveni Papyrus fragment, comparison of digital images (left) and RTI visualizations (right) in visible (top) and IR spectral area (below) (Image author's own).

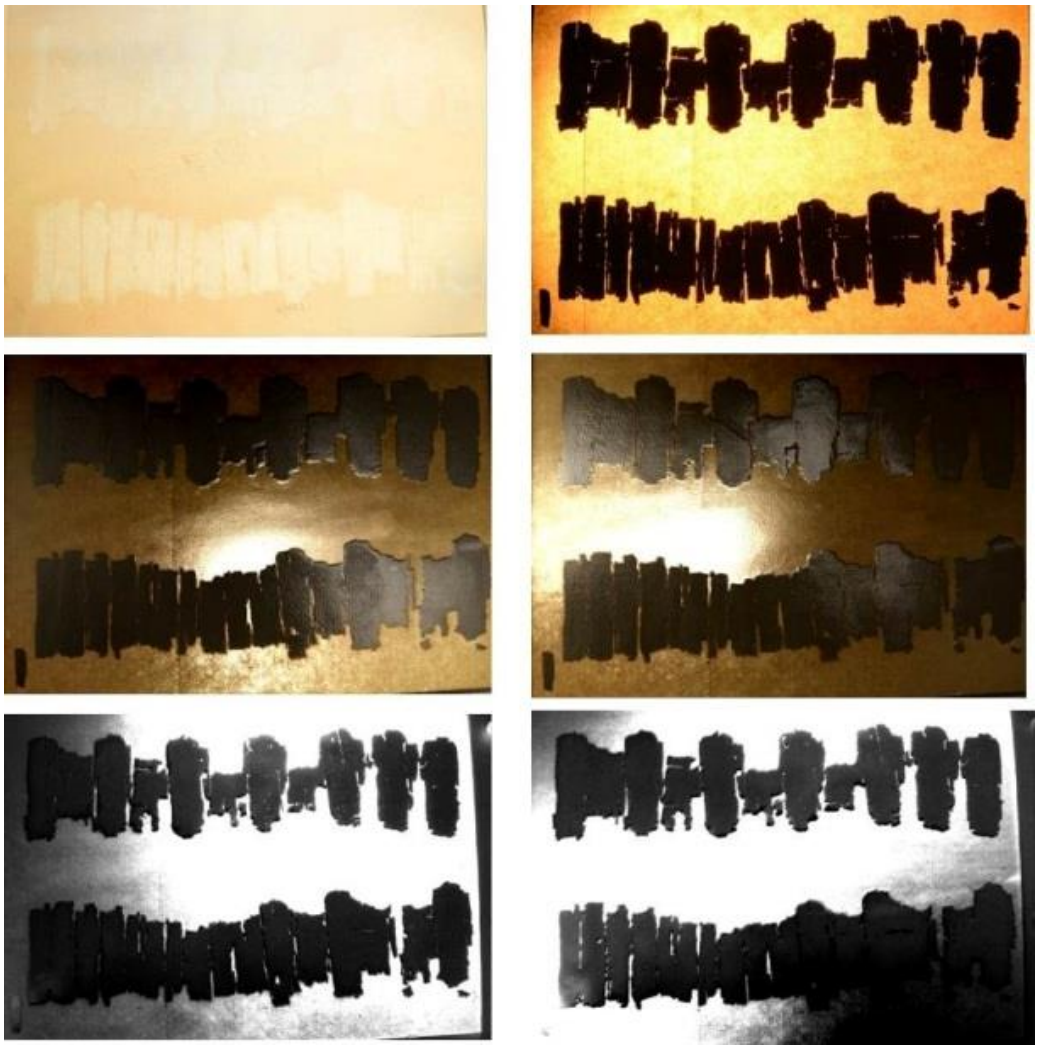


Figure 242: Derveni Papyrus fragment, digital image (top left) and trans illumination image (top right), trans illumination RTI renderings (middle) and trans irradiation RTI renderings (below) (Image author's own).

RTI enhances the readability of the texts and overcomes problems such as buckling and identification of edges. RTI in the infrared spectral region is particularly useful in case of blackened papyri in a carbonised state, as demonstrated by the IR-RTI renderings of the DP fragments. Trans irradiation RTI approaches can assist the detection of writings covered by backing materials. Also, RTI visualization enables the study of papyri without any interaction with the fragile papyrus material. This is of great importance because of the vulnerability of the papyri and the necessary manipulation involved in conventional artefacts examination. Virtual study of the papyrus not only protects its material integrity but is also more effective than physical examination because of the ability to virtually relight and apply different filters

using the available rendering modes so as to create the appropriate visualizations.

The potential of RTI applications in papyri is not limited to the enhanced legibility. RTI can successfully overcome the problems caused by the presence of the mounts regarding the visual analysis. Moreover, it is a powerful condition-reporting and documentation tool. For example joins, repairs, the state of preservation of the inks, misalignments, missing fibres and patterns can be emphasized in RTI visualizations. The application of microscopic RTI is a promising technique for the study of the papyri. It is expected, based on research with other materials, that the results of microscopic examination of abraded surfaces of palimpsests and corrosive inks would be enhanced by micro RTI.

The synergy of RTI, infrared imaging and trans illumination-irradiation enhances the readability of texts and assists the overall diagnostic examination of the papyrus, the examination of the manufacture techniques, the determination of its condition and its possible conservation needs. The resulting range of views of the Derveni papyrus increase our understanding of its artistic, historic and cultural heritage significance, and are useful for documentation, presentation, and communication and research purposes. Considering the low cost of the necessary equipment, the freely available software for processing and viewing *rti and/or *ptm files, the low level of expertise necessary for data capture in addition to the flexibility of RTI technology, which can adopt different set ups in order to cover the visualization needs of artefacts of different type, there is no doubt that RTI is a very useful methodology for documentation and recording. The application of the technique in the infrared spectral area demonstrate RTI's potential in diagnostic documentation and condition reporting, while trans illumination and irradiation RTI makes possible the visualization of features hidden behind backing materials. The enhanced readability of RTI snapshots compared to digital images offers the opportunity for enhanced optical character recognition of ancient texts, especially those in a poor state of preservation. The increased interest of the scientific community in the development of OCR software capable of reading ancient Greek, and the modern text mining

approaches, used in combination with the advanced RTI visualizations can assist the study of ancient texts.

5.3.2.2.6 Metals

In metals RTI visualization emphasize patinas, encrustations and depositions, pitting, cracking, crevices and warts, decoration, manufacture details, scratches and losses, assisting in understanding the artefact and its condition.

Bronze fragmentary artefacts from tomb Z visualised in RTI form demonstrate the advanced documentation and examination potential (Figures 243-244)[44]. Microscopic details offer an insight in manufacture details, striations and enable the examination of small fragments (Figure 245). Handling can endanger fragile fragments such as the gold gilded bronze leaf, originally part of a wreath. RTI visualization ensures accessibility to the archaeological material for conservators, archaeologists, curators and finds specialists without human object interaction (Figure 246).

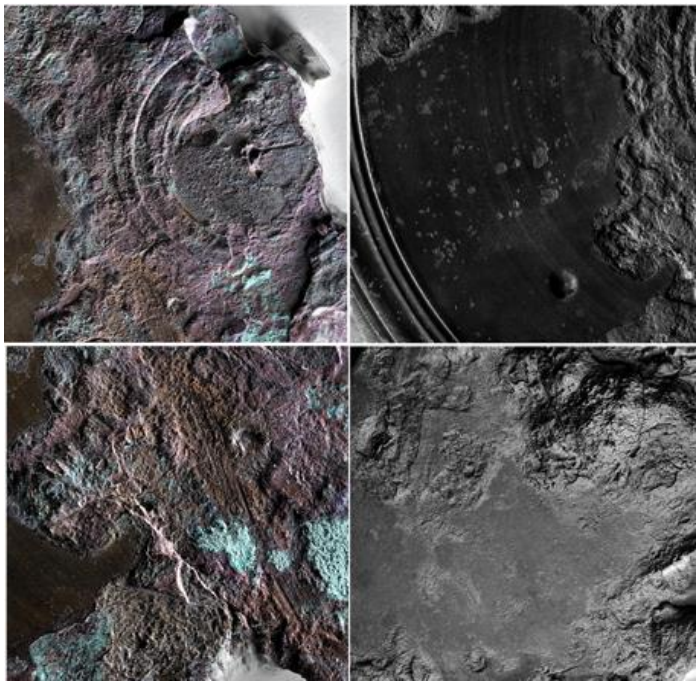


Figure 243: Bronze mirror, fragment, Z32. RTI visualization of details (Image author's own).

[44] See Digital Library, folder section5.3, files AMTH_GR_COP_Z32a_VIS-MA-H.rti, AMTH_GR_COP_Z32a_VIS-MI-H.rti and AMTH_GR_COP_Z32b_VIS-MA-H.rti

Figure 244: Bronze female head Z13. Digital image and RTI visualizations (Image author's own).

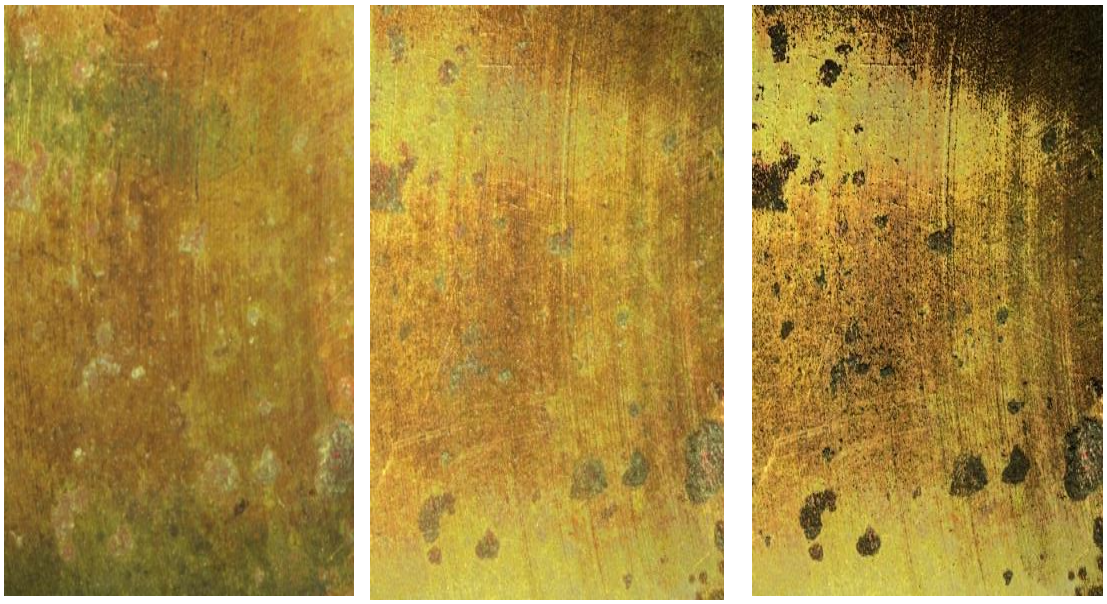


Figure 245: Bronze mirror, fragment, Z32. Microscopic detail. Visible area: 1,2 cm. Microphotograph (left) and RTI (middle, right) (Image author's own).

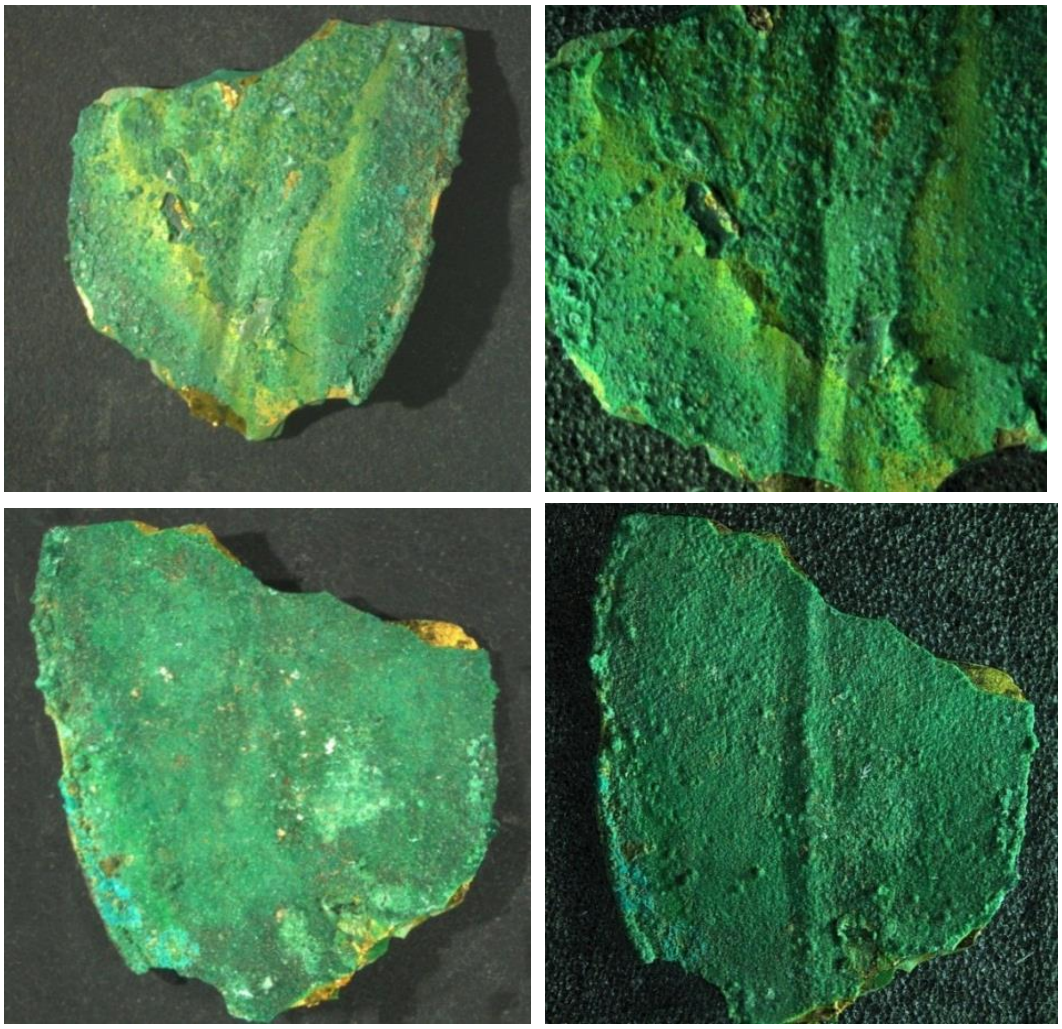


Figure 246: Gold gilded bronze leaf, part of a wreath. Fragment 1cm. Digital images (left) and RTI visualizations (right) (Image author's own).

In iron artefacts RTI leads to better understood and more advanced documentation of depositions and encrustations, physical damage characterization (Figure 247), decorative elements, surface features (Figure 248), manufacture or fabrication and previous treatment evidence (Figure 249)[45]. Similarly RTI is useful in case of silver artefacts, not only because of their reflective optical properties but also because of their physical characteristics (material softness). Microscopic RTI proved to be a valuable tool for documentation and condition reporting of a group of highly corroded and burnt gilded pieces of silver sheet in circular shape with repoussé scene of a Macedonian shield (Themelis and Touratsoglou, 1997). It reveals minor

[45] See Digital Library, folder section5.3, file AMTH_GR_COM_B118_VIS-MA-H.ptm

anomalies, scratches, gaps and pits, assisting physical damage examination and characterization. Decorations elements of low relief become apparent and are distinguished from depositions, encrustations or corrosion. Areas with striped texture on the backside of the discs may indicate contact with textile (Figures 250-252)[46].

Figure 247: Iron fragment. Digital images (top) and RTI visualization (down) (Image author's own).

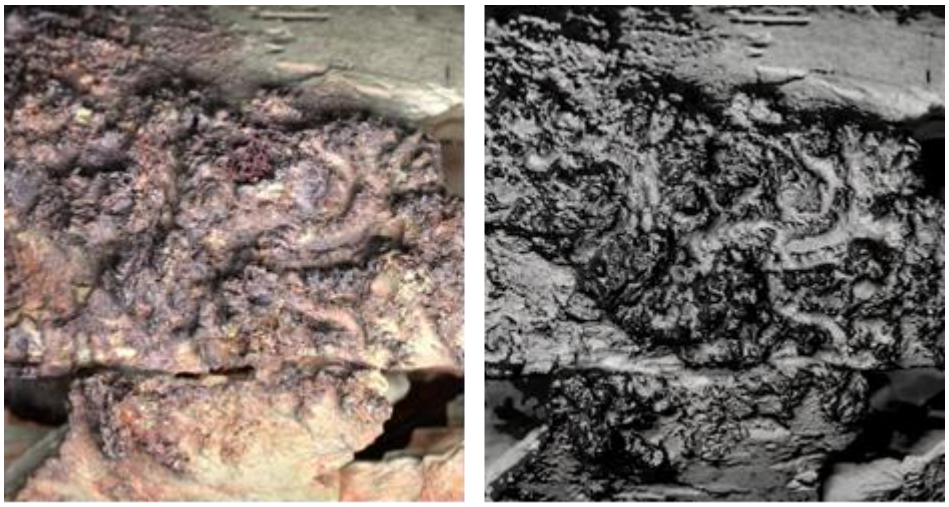


Figure 248: Bone handle with iron decoration. RTI visualizations (Image author's own).

[46] See Digital Library, folder section5.3, file AMTH_GR_SIL_A19a_VIS-MI-MD1.ptm, AMTH_GR_SIL_A19b_VIS-MI-MD1.rti and AMTH_GR_SIL_A19c_VIS-MI-MD1.rti

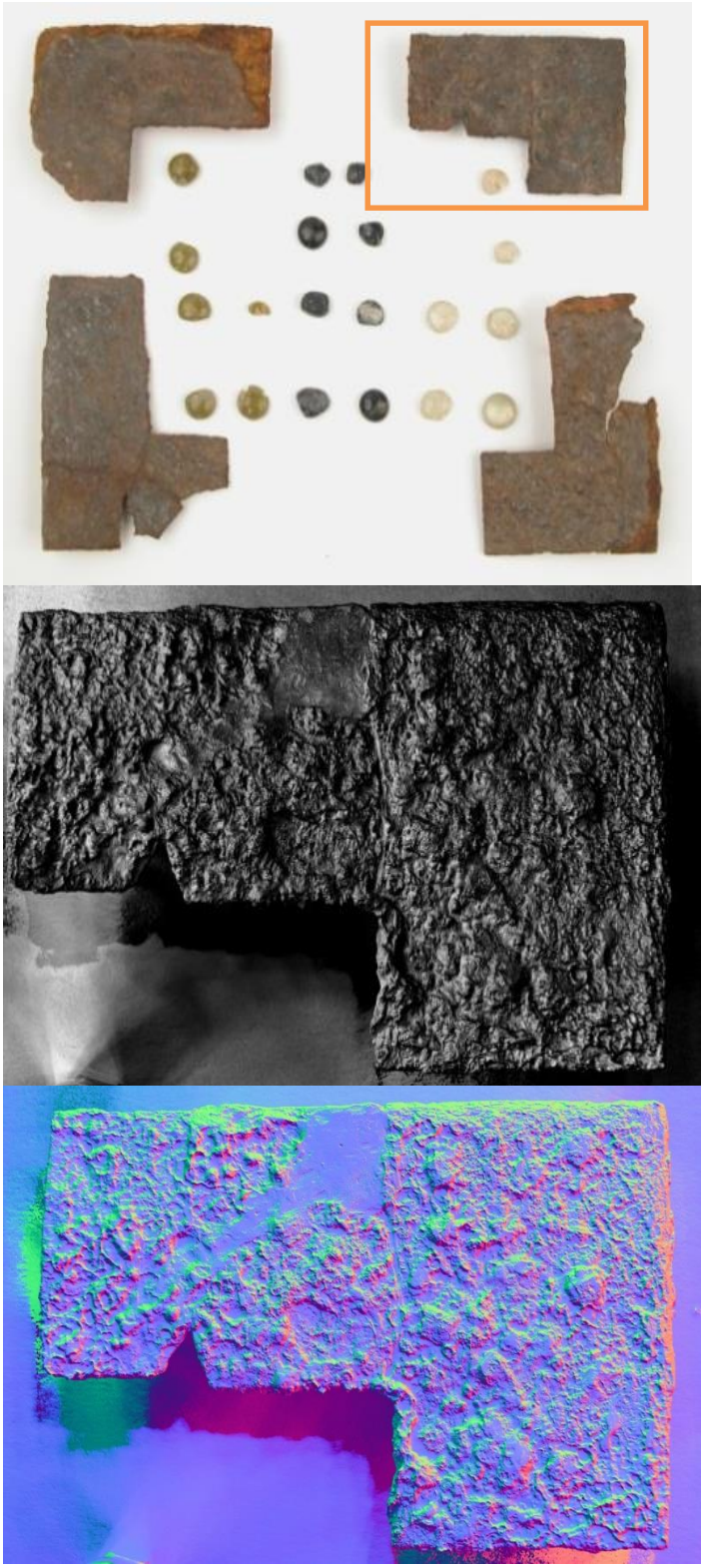


Figure 249: Board fragment. Digital image (top) and RTI visualizations (middle) and normal map (down) (Image author's own).

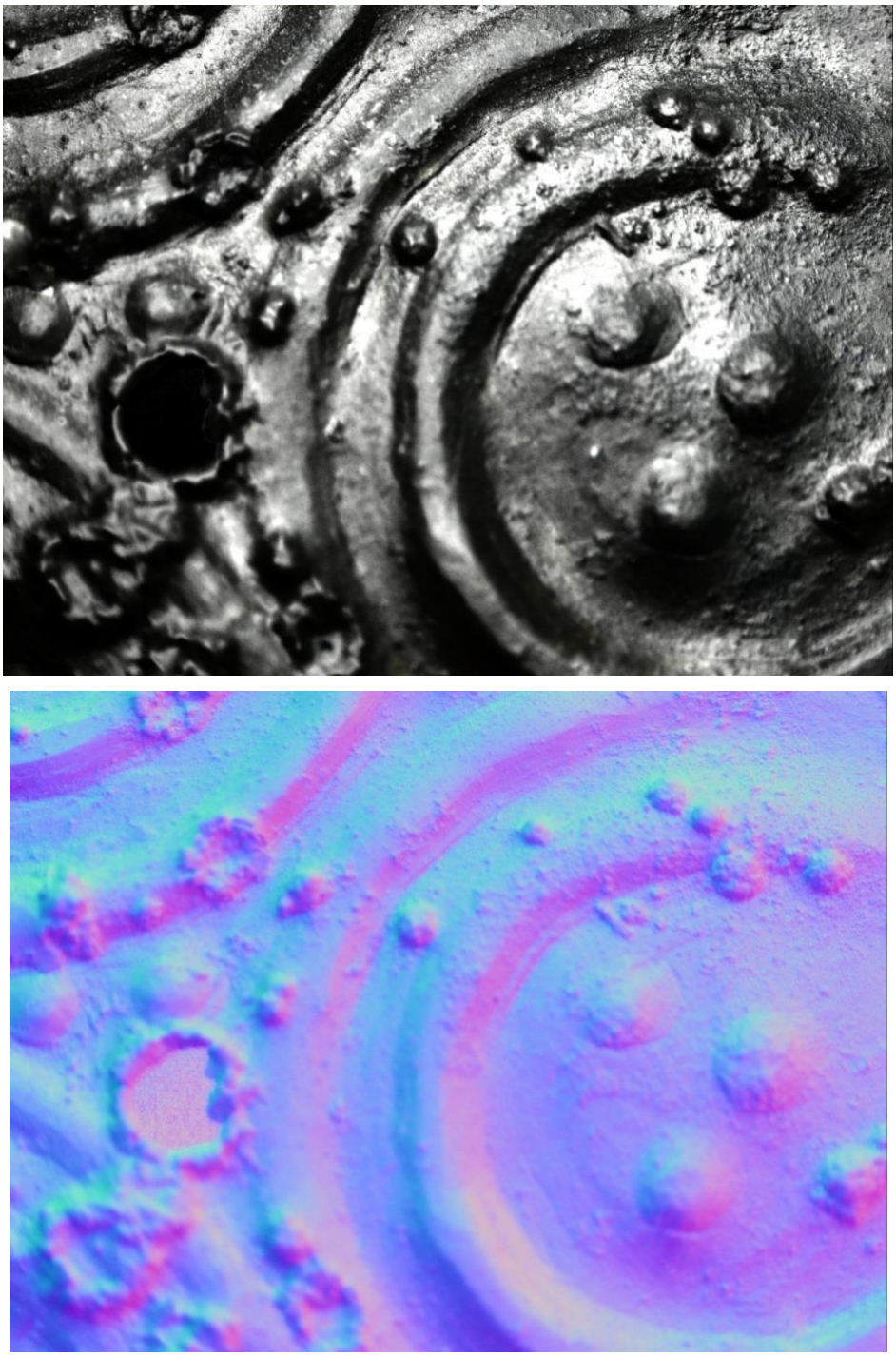


Figure 250: Gold gilded silver sheet in the shape of shield with scene of a Macedonian shield, diameter 3,6 cm. RTI visualizations (Image author's own).

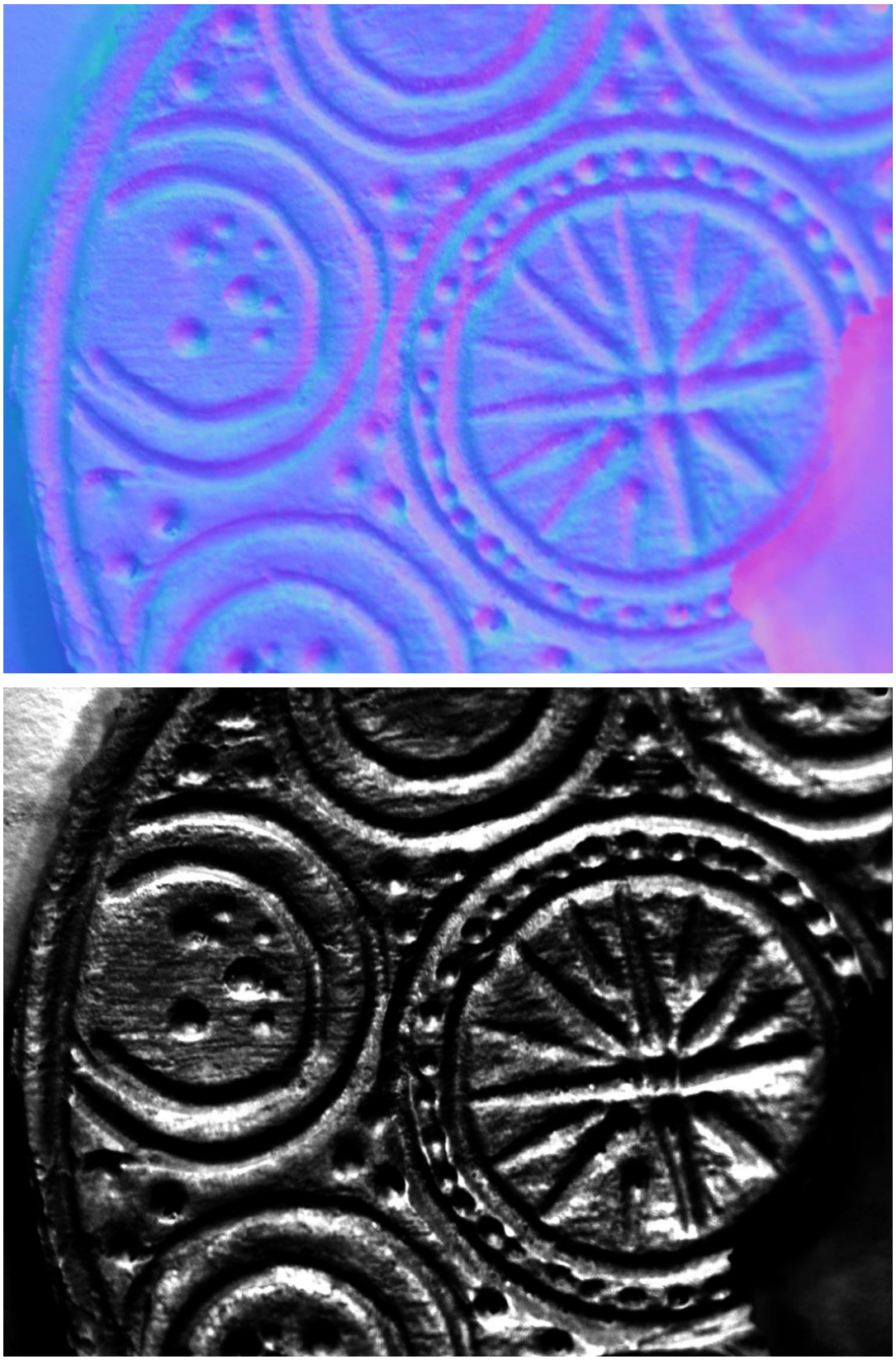


Figure 251: Microscopic image (top) and RTI visualization (below) (Image author's own).

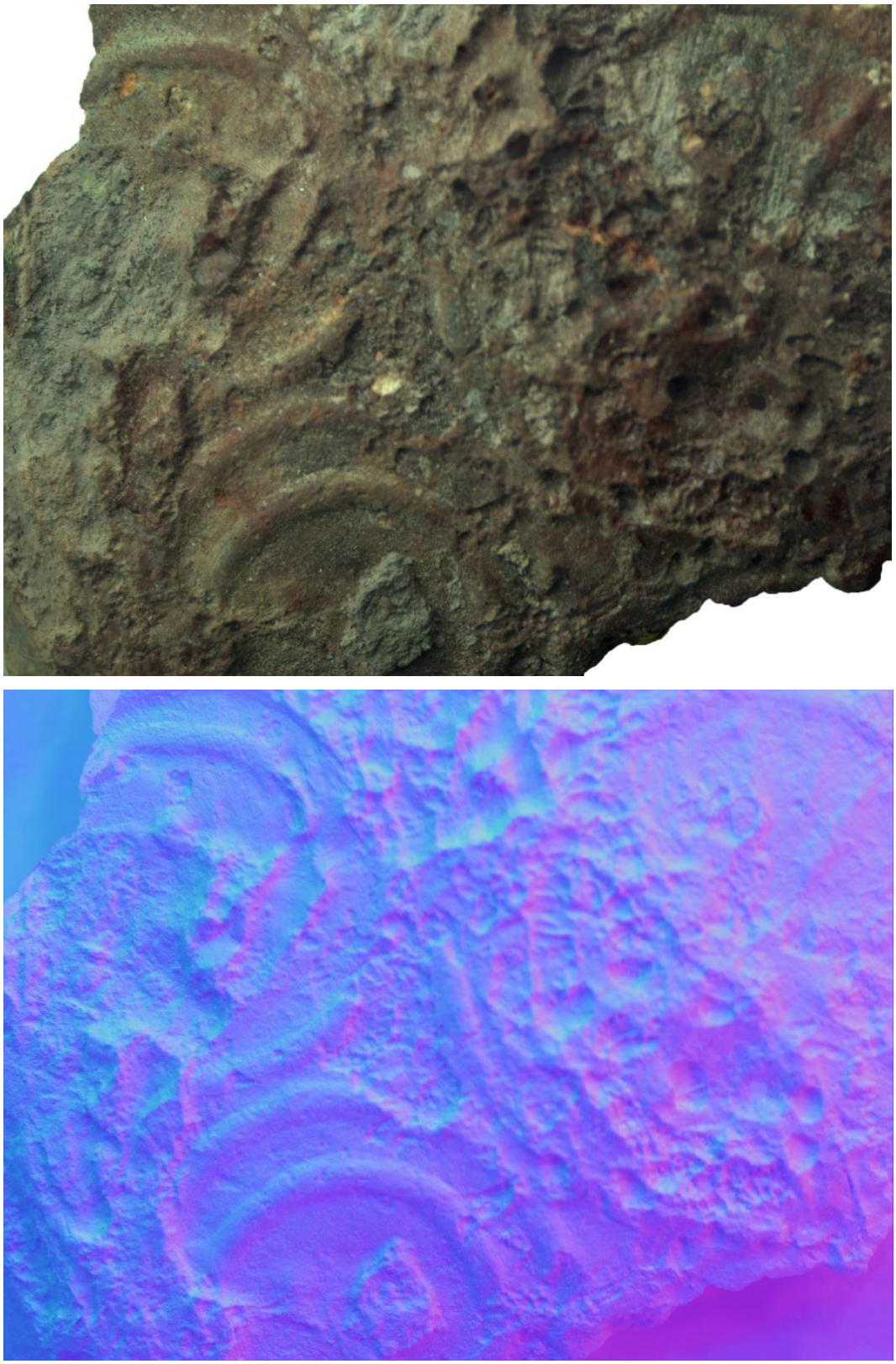


Figure 252: Microscopic image (top) and RTI visualizations (middle, below) (Image author's own).

5.3.2.3 Numismatics

RTI's contribution in numismatics will be analysed in this section, focusing on identification, condition reporting and conservation monitoring.

5.3.2.3.1 Identification

Identification of coins due to their small size and the minor low relief details is a demanding task. The highly reflective gold and silver surface, or poor states of preservation, adds an extra level of complexity. A significant methodological improvement for effectively capturing minor details is the application of microscopic dome RTI. Characteristic examples which demonstrates microscopic RTI's efficiency in coins' visualization is a gold stater from Derveni Tomb D. On the reverse of the coin the capital double I legend is unclear in the microphotograph, however this detail is emphasized on the microscopic RTI visualization[47] (Figure 253). The legend on the silver diobol of the Macedonian Kingdom is not recognizable in the digital images, but becomes legible in the RTI renderings, created using the mini-dome method and macroscopic means. Notable is the fact that each letter is approximately 1mm (Figure 254).

Figure 253: 1/8 stater of Phillip II, gold, reverse, Derveni, Tomb D. Visualization after conservation treatment. RTI visualization (Image author's own).

[47] See Digital Library, folder section5.3, file AMTH-GR_GOL_D2_rvs_AC_VIS-MI-MD1.ptm

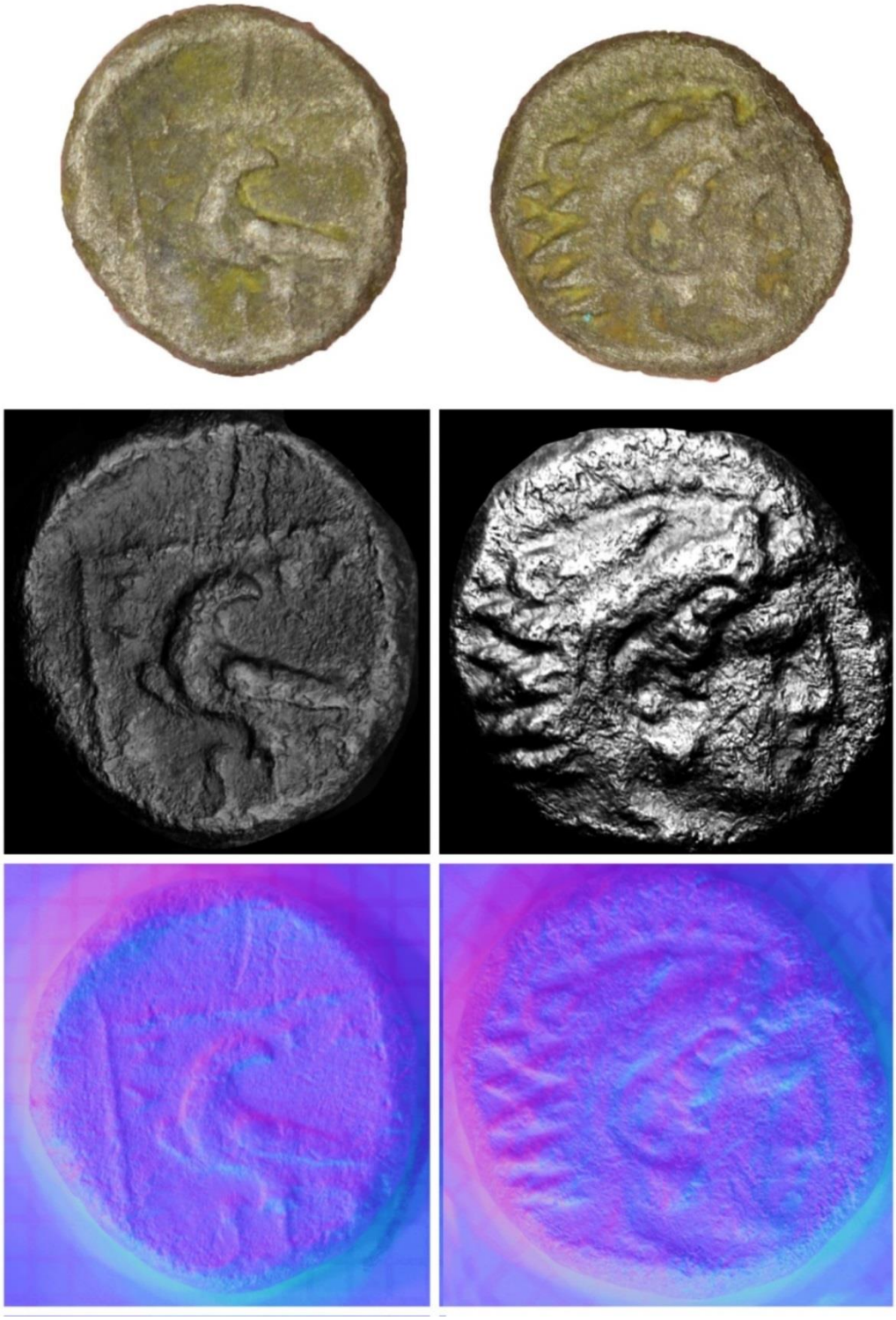


Figure 254: Silver diobol of Macedonian Kingdom (Coin no 13). Archaeological Museum of Amphipolis. Visualization before conservation treatment. Digital images (top) RTI visualizations in specular enhancement mode (middle) and normal maps (below) (Image author's own).

RTI visualization proved effective, not only in the case of reflective materials and small coins, such as diobols and staters, but also assisted the identification and dating of corroded and worn coins. Legends become legible and designs are emphasized in RTI visualizations, even if the surface of the coin is worn (Figure 255), pitted [48](Figures 256-258) and has suffered losses[49] (Figure 259). In some cases the poor preservation of the coin makes its identification impossible, but RTI still provide a clearer picture of its texture, leading to enhanced visualization. The technique proved particularly interesting not only after cleaning but also before conservation treatment. Although the coin surface is partly covered by corrosion products the legends and designs become discernible[50] (Figures 260-261).

Figure 255: Copper alloy coin (Coin no 8). Diam. 14mm. Archaeological Museum of Amphipolis. Visualization after conservation treatment. RTI visualizations (top) and normal maps (below) (Image author's own).

[48] See Digital Library, folder section5.3, file AMA-GR_SIL_20_rvs_AC_VIS-MA-MD2.rti
[49] See Digital Library, folder section5.3, files AMA-GR_COP_19_rvs_BC_VIS-MA-MD2.rti and AMA-GR_COP_19_obv_BC_VIS-MA-MD2.rti
[50] See Digital Library, folder section5.3, files AMA-GR_COP_23_obv_BC_VIS-MA-MD2.rti and AMA-GR_COP_25_rvs_BC_VIS-MA-MD2.rti

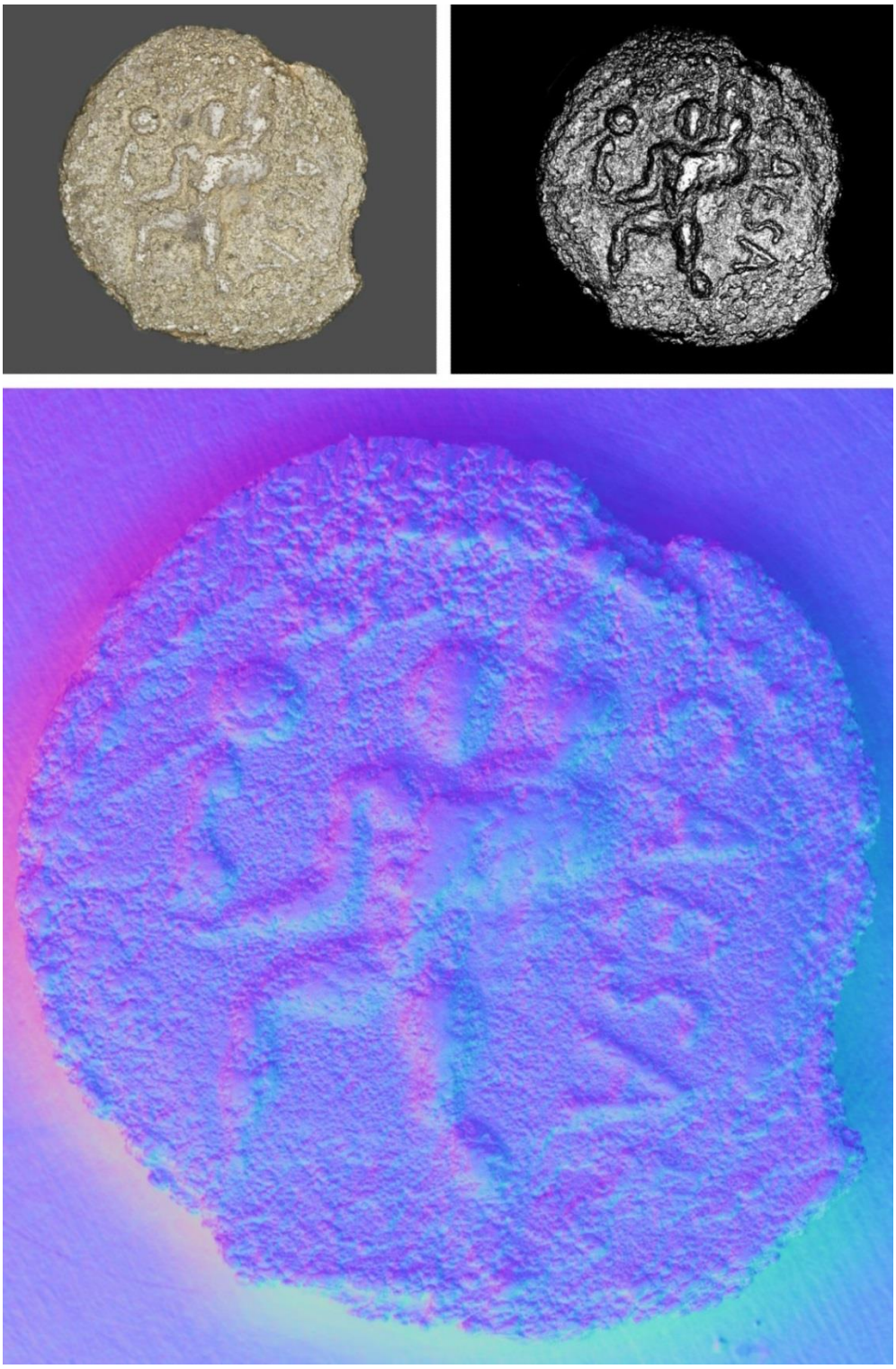


Figure 256: Silver roman imperatorial denarius (Coin no 20). Diam. 19 mm. Archaeological Museum of Amphipolis. Visualization after conservation treatment. Digital image (top left) and RTI visualization in specular enhancement mode (top right) and normal map (below) (Image author's own).

Figure 257: Silver coin. Possibly denarious of the family of Repousias (Coin no 21). Diam. 17 mm . Archaeological Museum of Amphipolis. Visualization after conservation treatment.Digital image (top left), normal map (top right) and RTI visualization in specular enhancement mode (below) (Image author's own).

Figure 258: Copper alloy coin (Coin no 1). Diam. 18mm. Archaeological Museum of Amphipolis. Visualization after conservation treatment. Digital images (top) RTI visualizations in specular enhancement mode (middle) and normal maps (below) (Image author's own).

Figure 259: Copper alloy coin (coin no 19). Archaeological Museum of Amphipolis. Visualization before conservation treatment Digital images (top), RTI visualizations in specular enhancement mode (middle) and normal maps (below) (Image author's own).

Figure 260: Copper alloy coin. (Coin no 23). Diam. 26mm. Archaeological Museum of Amphipolis. Visualization before conservation treatment Digital image (left), RTI visualization in specular enhancement rendering mode (right) (Image author's own).

Figure 261: Copper alloy coin (coin no 25). Diam. 26mm. Archaeological Museum of Amphipolis. Visualization before conservation treatment. Digital images (top), RTI visualizations in specular enhancement mode (middle) and normal maps (below) (Image author's own).

One of the most interesting findings of the numismatic RTI case study emerged from comparison with the RTI's before and after treatment. Although the digital images of the coins before and after treatment differ considerably, with the latter being far more informative about the coin, this is not always the case for the RTI visualisations. In cases of uniform corrosion RTI visualizations before cleaning succeed in revealing the surface topography of the coin. The comparison of pre and post treatment RTI visualization reveals minor differences. Post treatment digital images of the coins reveal the same data for coins identification with pre-treatment RTI visualizations[51] (Figures 262-263).

[51] See Digital Library, folder section5.3, files AMA-GR_COP_6_obv_AC_VIS-MA-MD1.rti, AMA-GR_COP_6_obv_BC_VIS-MA-MD1.rti,

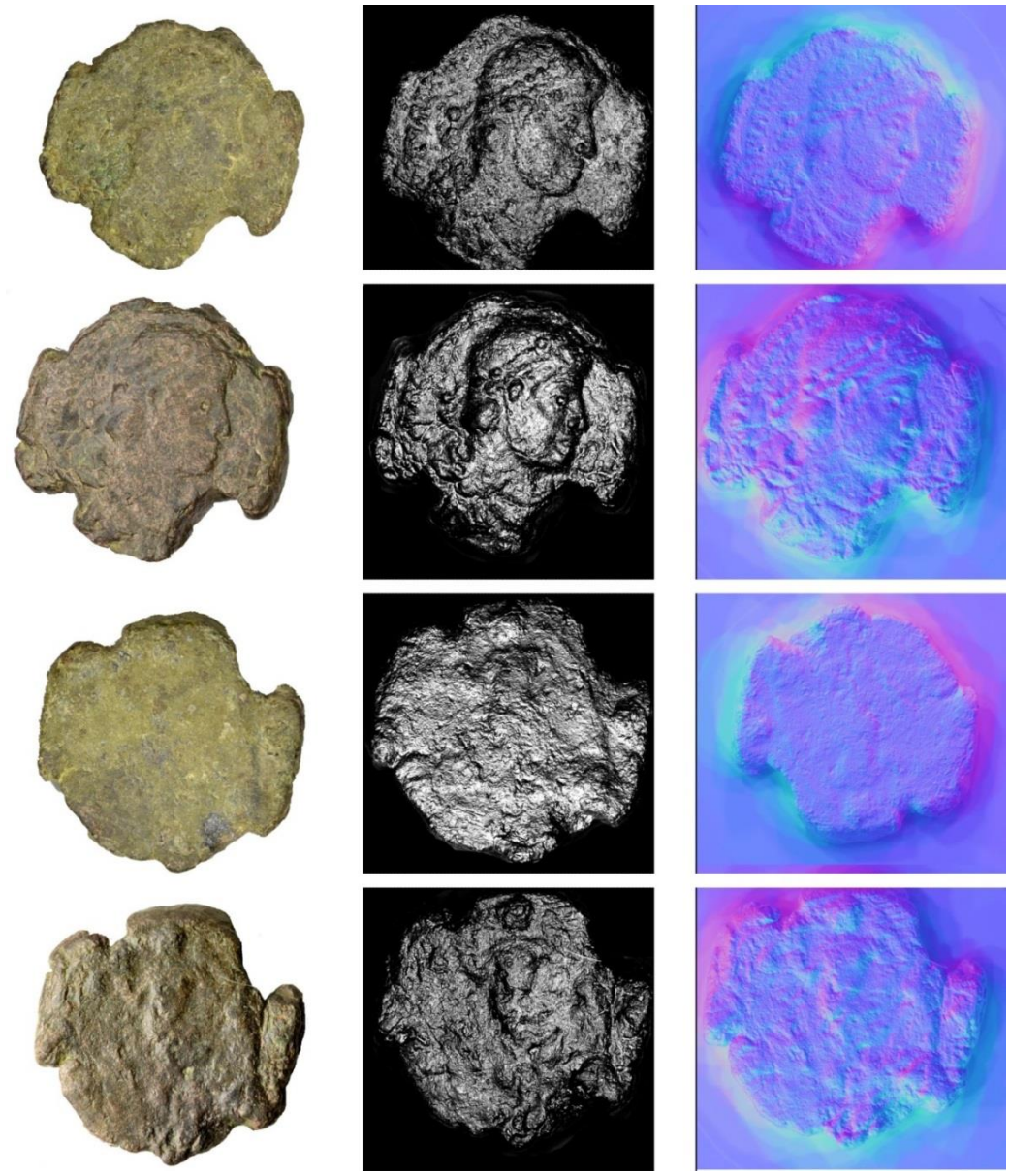


Figure 262: Copper alloy coin. (Coin no 6). Diam. 18mm. Archaeological Museum of Amphipolis. Visualization before and after conservation treatment. Digital images before and after conservation (left) RTI visualizations (middle) and normal maps (right) (Image author's own).

AMA-GR_COP_6_rvs_AC_VIS-MA-MD1.rti and AMA-GR_COP_6_rvs_BC_VIS-MA-MD1.rti

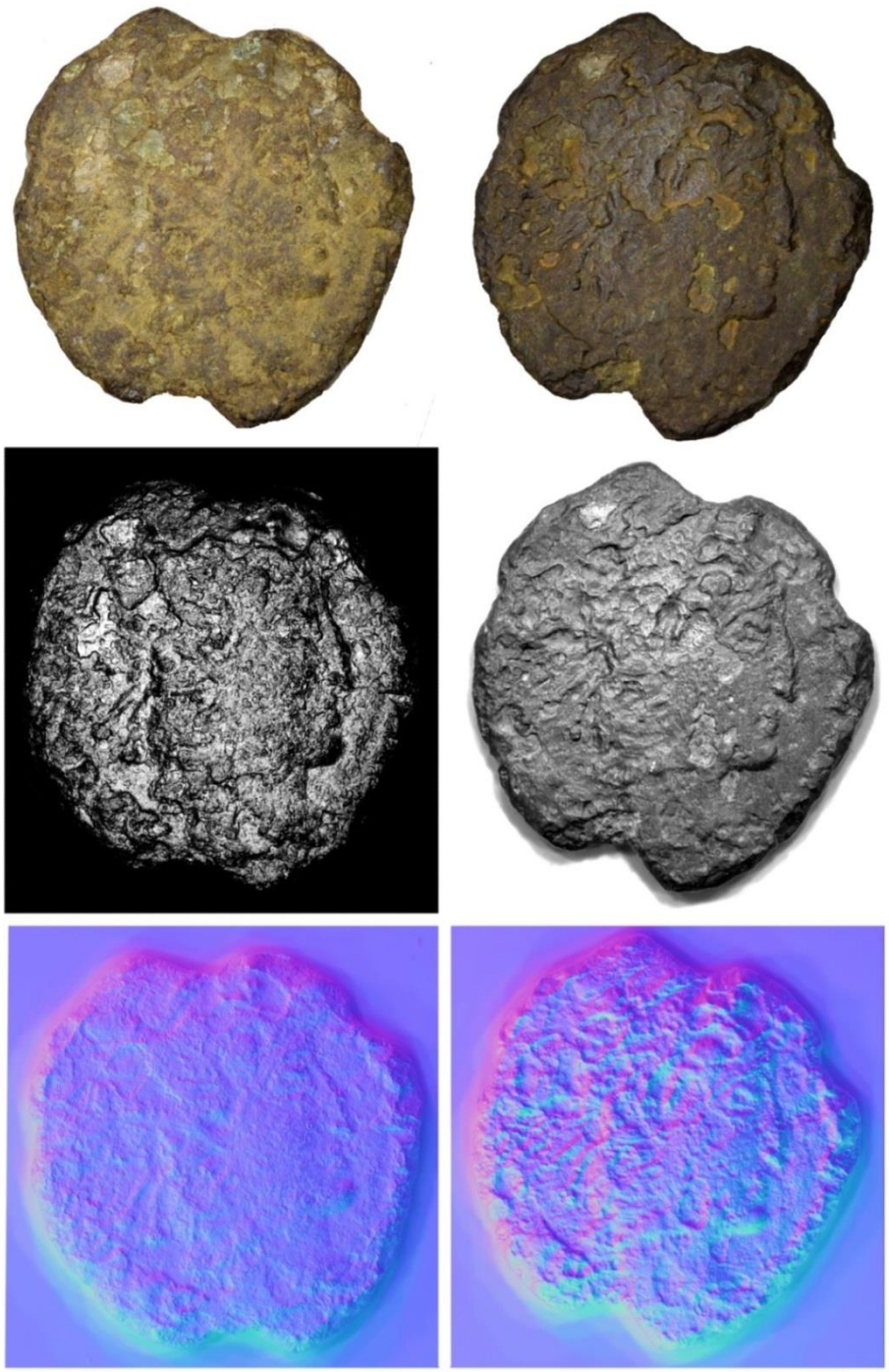


Figure 263: Copper alloy coin (Coin no 7). Diam. 15mm. Archaeological Museum of Amphipolis. Visualization before and after conservation treatment. Digital images (top) RTI visualizations in specular enhancement mode (middle) and normal maps (below) (Image author's own).

5.3.2.3.2 Condition reporting

RTI not only assists identification and dating but also enhances examination and condition reporting of surface effects, such as corroded (Figure 264), pitted surfaces with encrustations - depositions and scratches (Figures 265-266)[52] and surface loss, caused due to ageing and/or burial or contact with other materials or due to conservation treatment. The most characteristic example of the latter is the silver roman imperatorial denarius of Julius Caesar minted in North Africa in 47–46 BC. The stripped, porous, rough surface, which was emphasised in RTI visualizations, is indicative of chemically cleaning (Figure 256).

Figure 264: Copper ally coin (coin no 12). Diam. 18mm. Archaeological Museum of Amphipolis. Visualization after conservation treatment. Digital images (left) and RTI visualizations (right) (Image author's own).

[52] See Digital Library, folder section5.3, files AMA-GR_COP_18_obv_AC_VIS-MA-MD2.rti, AMA-GR_COP_18_obv_BC_VIS-MA-MD2.rti and AMA-GR_COP_18_rvs_AC_VIS-MA-MD2.rti and AMA-GR_COP_18_rvs_BC_VIS-MA-MD2.rti

Figure 265: Copper ally coin (Coin no 18). Diam. 23mm. Archaeological Museum of Amphipolis. Visualization before conservation treatment. Digital image (top left), RTI visualization (top right) and normal map (below) (Image author's own).

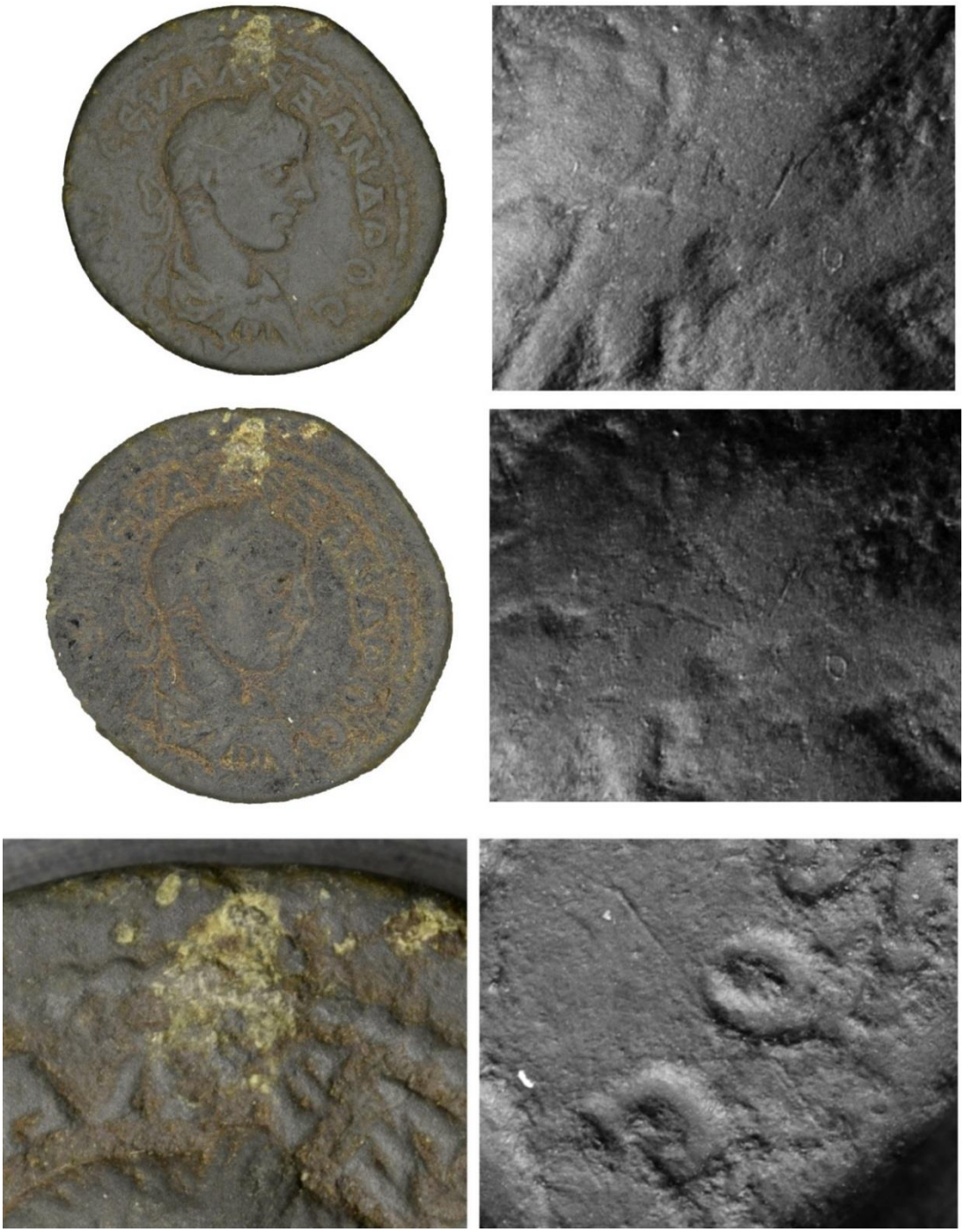


Figure 266: Copper ally coin (Coin no 18). Diam. 23mm. Archaeological Museum of Amphipolis. Visualization before conservation treatment. Digital image (top left) and RTI visualizations (Image author's own) (Image author's own).

RTI visualisations of coins from the Simmoneschi Collection (Pisa, Italy), available on line through the interactive kiosk (http://vcg.isti.cnr.it/PalazzoBlu/) developed by the CNR, gave the opportunity for detecting these degradation phenomena on coins via a completely virtual examination. Although the main idea of the developers were the opening of the collection to the public, the web RTI visualizations of the coins open new horizons for comparison of preservation and conservation treatment methodologies, and can act as a catalyst for an open conservation dialog regarding conservation and numismatics research. Characteristic examples of interest from a conservation condition reporting point of view were the losses, depositions, scratches and cracks detected in coins' surfaces, features which cannot be visualised effectively in digital images (Figures 267-270).

Figure 267: Silver coin, Etruscan, possibly from Luca. Diam. 22mm. The Simmoneschi Collection, Exh. No 27. Coin as if lighted from above (left) and RTI visualizations (right). RTI file available online through http://vcg.isti.cnr.it/PalazzoBlu/

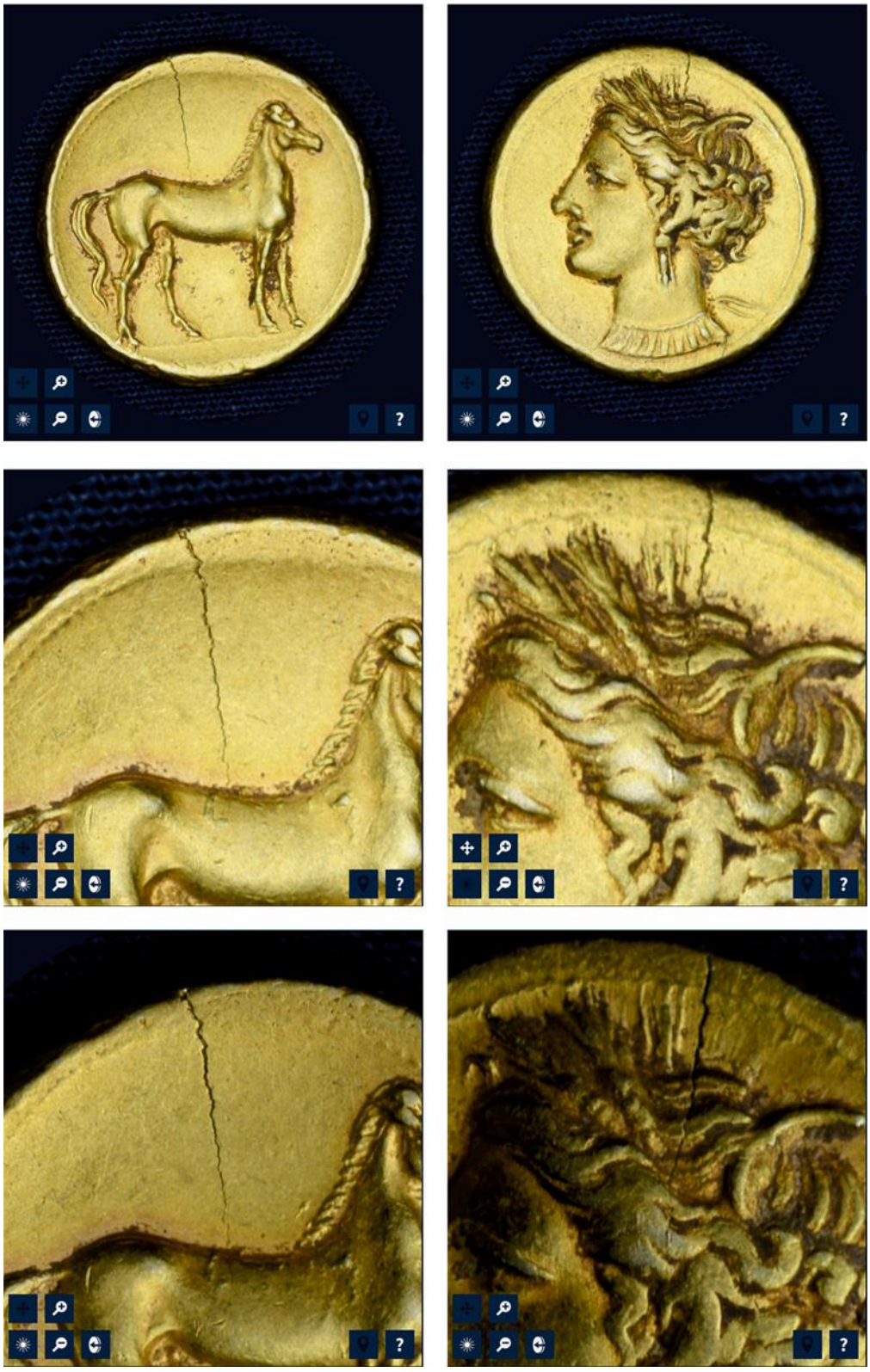


Figure 268: Gold coin, Carthaginian series. Diam. 20mm. The Simmoneschi Collection, Exh. No 38. Coin as if lighted from above (top and middle) and RTI visualizations (below). RTI file available online through http://vcg.isti.cnr.it/PalazzoBlu/

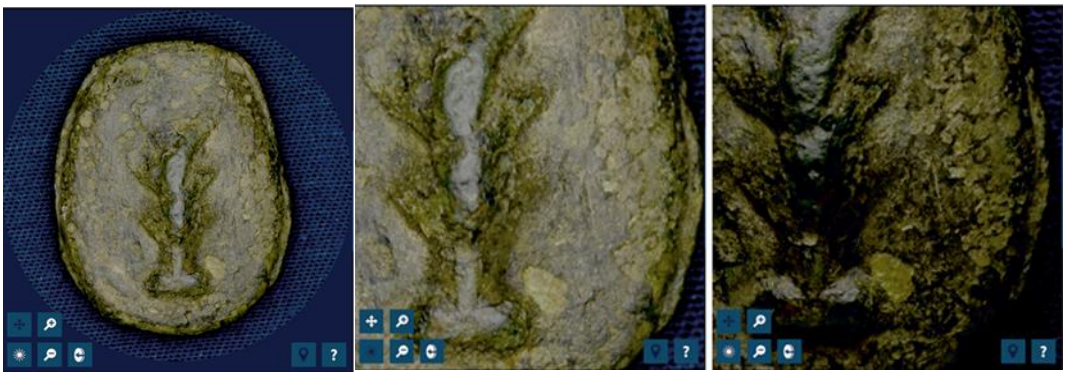


Figure 269: Cast bronze coin. Oval sextans. Etruscan. Diam. 29mm. The Simmoneschi Collection, Exh. No 30. Coin as if lighted from above (left) and RTI visualizations (middle, right). RTI file available online through http://vcg.isti.cnr.it/PalazzoBlu/

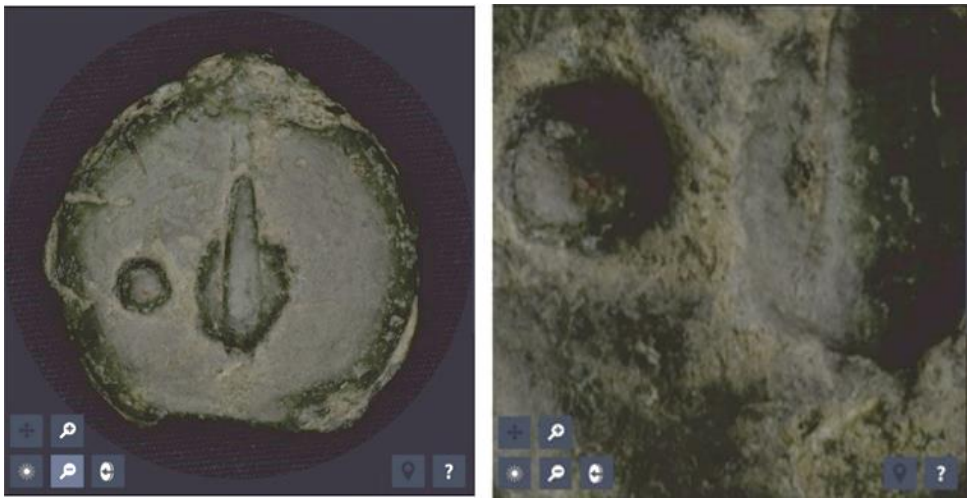


Figure 270: Cast bronze coin. Uncia. Diam. 27mm. The Simmoneschi Collection, Exh. No 2. Coin as if lighted from above (left) and RTI visualizations (right). RTI file available online through http://vcg.isti.cnr.it/PalazzoBlu/

RTI ability to underline surface variations can be helpful to the examination of coins, a process that may lead to interesting conclusions about various aspects of the coin, such as its manufacture and use. For example, enhanced RTI visualization can help conservators distinguish cracks among other defects, study their form and potentially reach conclusions about a coin's manufacture. For example, it is known that surface cracking is strongly connected to minting. According to the bibliography, radial cracking indicates coins

hammered to shape, while crack irregularities, such as those on Figure 271, are considered a result of striking (Goodbrown-Brown, 1998).

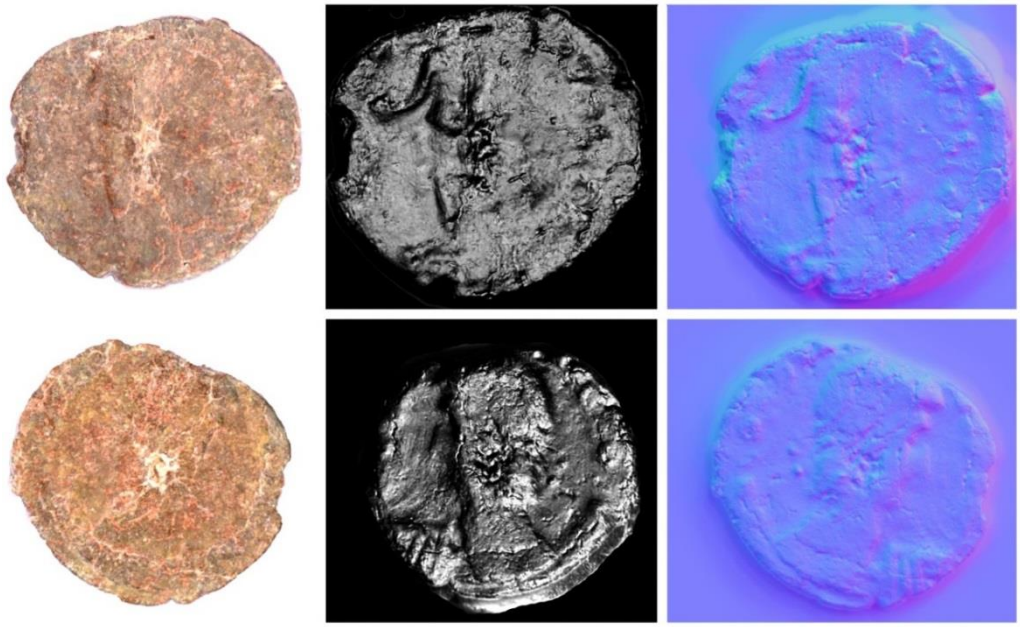


Figure 271: Copper alloy coin (coin no 3). Diam. 13mm. Archaeological Museum of Amphipolis. Digital images (left), RTI visualizations (middle) and normal maps (right) (Image author's own).

5.3.2.3.3 Conservation documentation and monitoring

RTI visualizations of coins before cleaning documented the state of conservation, while those captured after conservation intervention evaluate the success of such a treatment[53]. The goal of numismatic conservation is to remove the active corrosion products, which can cause further degradation, even under controlled environmental conditions, in addition to revealing the representations and legends. This helps safeguard material integrity, and to re-establish aesthetic values, so that the exhaustive examination of the coins' surface after conservation is imperative. Hence, RTI's ability to emphasize

[53] See Digital Library, folder section5.3, files AMA-GR_COP_22_rvs_AC_VIS-MA-MD2.rti, AMA-GR_COP_22_rvs_BC_VIS-MA-H.rti and AMA-GR_COP_23_rvs_AC_VIS-MA-MD2.rti, AMA-GR_COP_23_rvs_BC_VIS-MA-H.rti

texture is a valuable tool. For example, as shown in Figure 272-274, the relatively smooth surface obtained after treatment indicates that no further action was required, for preservation, identification or aesthetic reasons.

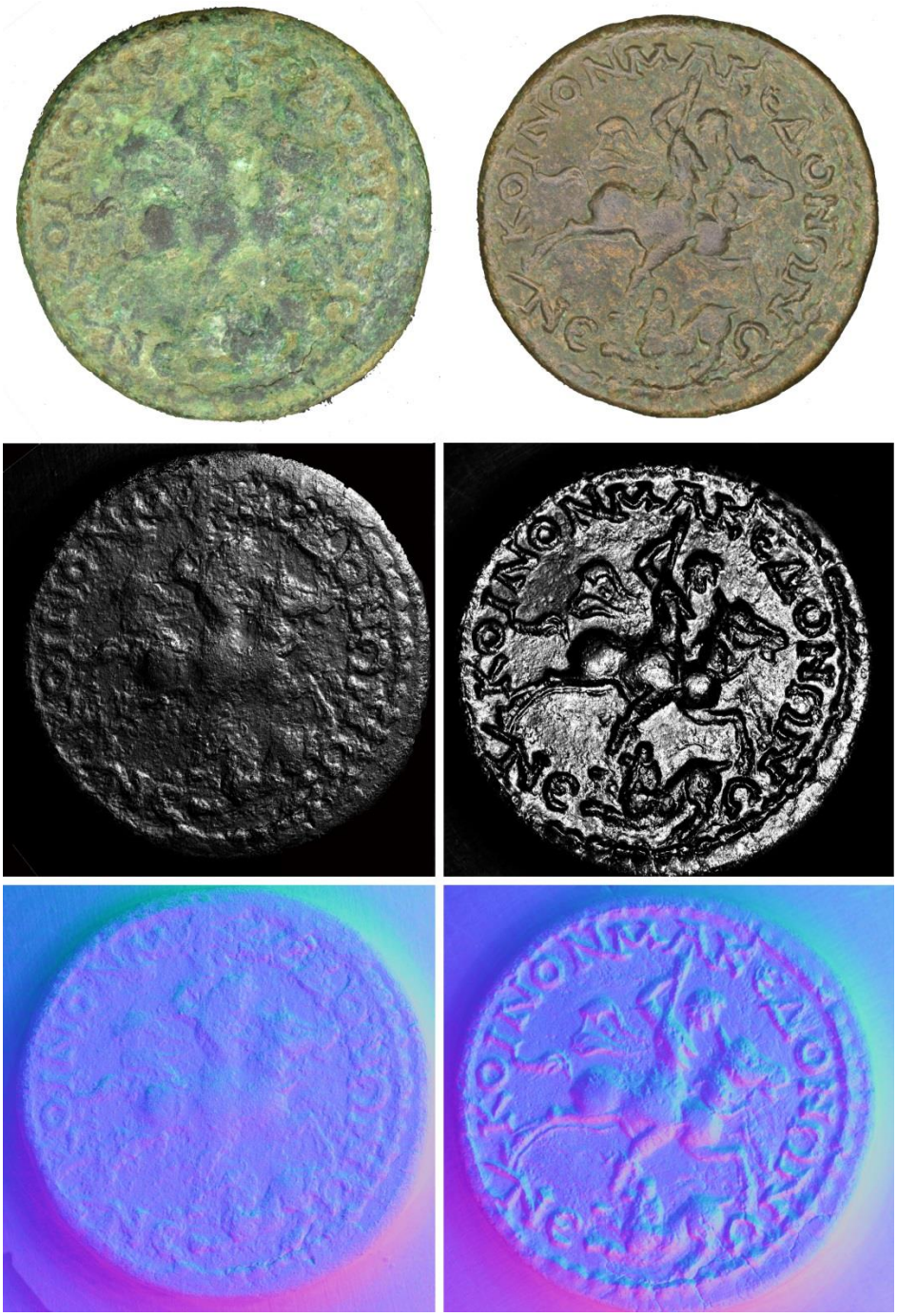


Figure 272: Copper alloy coin of the Koinon of Macedon. Diam. 26 mm. Coin no 23. Reverse digital images (left) and RTI visualization (middle) and normal maps (right) before conservation (top) and after conservation treatment (below) (Image author's own).

Figure 273: Copper alloy coin. Coin no 18. Diam. 23mm. Reverse. Digital images before and after treatment (top), RTI visualization (middle) and normal maps (below) (Image author's own).

Figure 274: Copper alloy coin. Diam. 22 mm. Coin no 22. (Image author's own).

Also, RTI visualizations of coins, not only pre- and post- but also during treatment, capture the coins' "museum life", an inseparable part of its biography, and can be used as means for cleaning monitoring and conservation documentation[54] (Figure 275-276). Taking into consideration that RTI viewing is comparable to the original artefact examination experience, the object visualization in relation to time and change before, after and during conservation intervention is recommended. This approach befits archaeological and conservation ethics and succeeds in capturing the objects "non-static" nature.

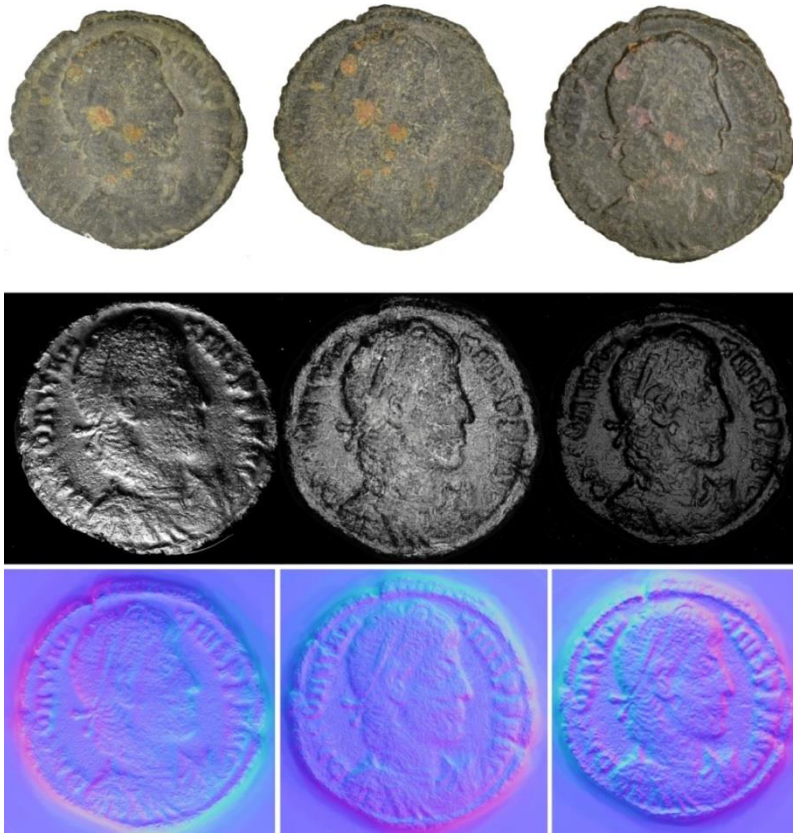


Figure 275: Copper alloy coin. Coin no 4. Diam. 17mm. Digital image before, during and after treatment (top) RTI visualizations (middle) and normal maps (below) (Image author's own).

[54] See Digital Library, folder section5.3, files AMA-GR_COP_4_obv_AC_VIS-MA-MD1.rti, AMA-GR_COP_4_obv_BC_VIS-MA-MD1.rti, AMA-GR_COP_4_obv_DC_VIS-MA-MD1.rti and AMA-GR_COP_5_obv_AC_VIS-MA-MD1.rti, AMA-GR_COP_5_obv_BC_VIS-MA-MD1.rti, AMA-GR_COP_5_obv_DC_VIS-MA-MD1.rti, AMA-GR_COP_5_rvs_AC_VIS-MA-MD1.rti, AMA-GR_COP_5_rvs_BC_VIS-MA-MD1.ptm and AMA-GR_COP_5_rvs_DC_VIS-MA-MD1.ptm

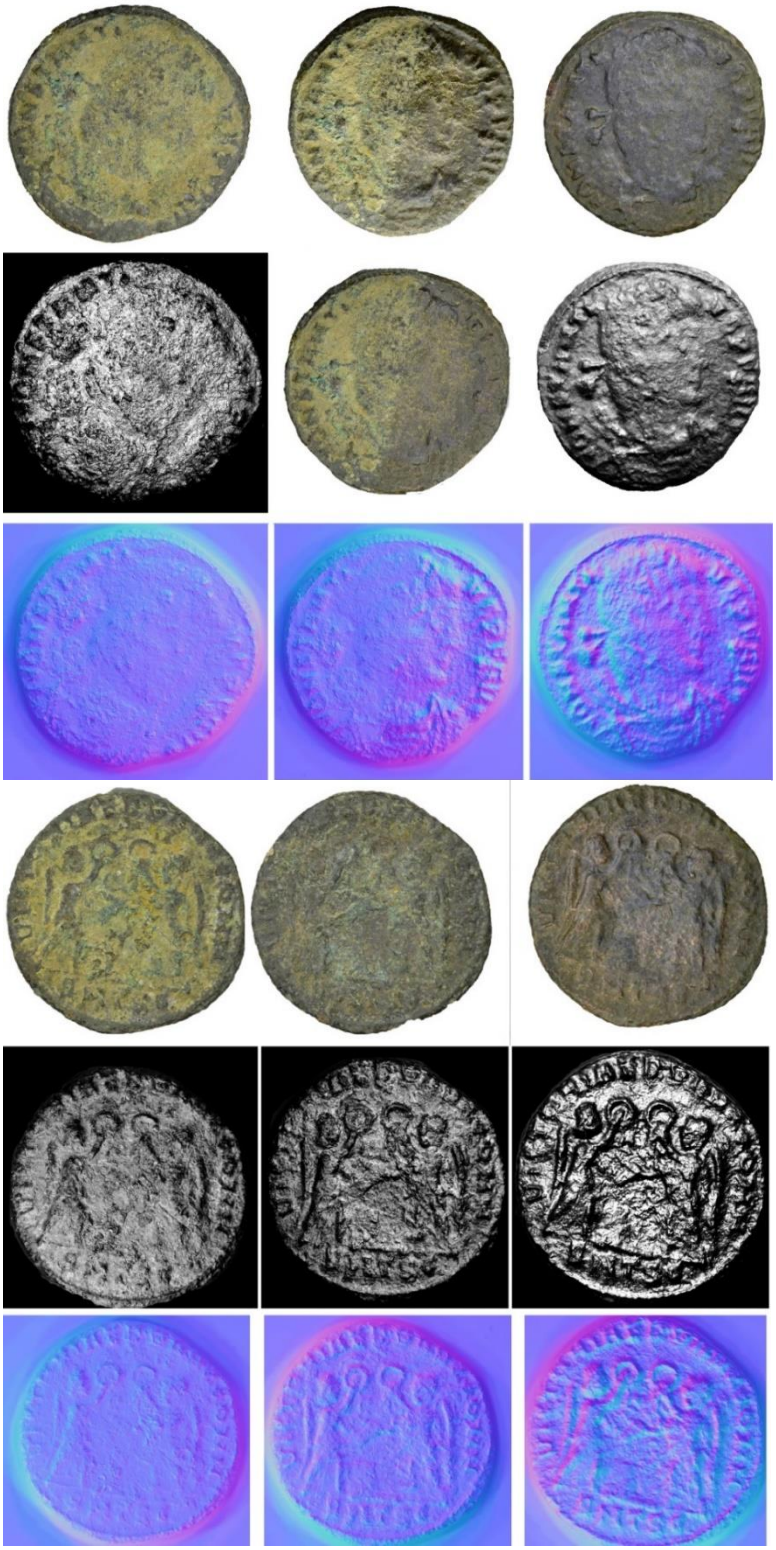


Figure 276: Copper alloy coin no 5. Diam. 22mm. Reverse (top) obverse (bellow). Digital images before (left), during (middle) and after mechanical cleaning (Image author's own).

5.3.2.4 Rendering modes

The RTI visualization may lead to images that present features different to the common digital images. Although this phenomenon is the power of the technique it does not come without its limitations. It is recommended for RTI users to address critically features which appear strange based on previous knowledge about artefacts, materials' optical properties, damage or alteration. The interpretation of such features requires special attention and, if possible, implementation of other techniques to avoid misleading conclusions.

There are no restrictions in the manipulation of RTI files, and every user can make its own discoveries, exploring the various components of artefacts. The crucial point in the whole process is to keep metadata for the visualizations produced by the software, including the *ptm and *rti general files and the single renderings (snapshots) from each lighting condition under each rendering mode employed. This approach is the logical and sophisticated manner of experiencing RTIs. If the metadata process is overlooked, the visualised digital artefact will display neither a useful nor a trustworthy version of the original, with limited research potential for the scientific community. The features included in the latest version of RTI viewer software are particularly helpful towards not only the annotation of RTI files but also the distribution of metadata about each rendering.

The quantity of artefacts captured and the variety of material and artefacts types allow us to reach generic conclusions about the application of rendering modes in RTI visualizations. This approach does not intend to restrict the interactivity of the RTI by proposing specific methodologies for viewing. The goal is to provide general recommendations so as to lead to more efficient and focused RTI experiences for museum professionals. For the purposes of the present study each RTI was viewed initially in the default rendering view. According to the findings of this first inspection, attention was focussed on specific portions of the RTI image using zoom and pan. Then different rendering modes were tested in order to virtually investigate features of the artefacts under examination.

In the RTI examples from the Derveni cemetery the specular enhancement rendering mode was used in the vast majority of material and artefacts types

and contributed significantly in the interpretation of RTI's. In stone RTI visualisations the specular enhancement rendering mode was used for the improved representation of the base shape as well as for the irregularities on the stone surface, encrustations and depositions. In the glass alabastra the specular enhancement enabled better visualisation of the feather pattern. For ceramics it provides advanced documentation of the red-figure technique features, such as the relief lines, and in the case of the ceramics roundels enabled the visualisation of the facial characteristics. Also, it helps discrimination between areas with different optical properties, assisting in that way the differentiation of materials. It is particularly useful for the study of coins. In skeletal material the specular enhancement successfully documents the presence of surface deformation, damage, losses and scratches. In documentary artefacts, and especially the Derveni Papyrus, it gave valuable information about the geometric characteristics and shape of the fragments.

The specular enhancement mode was largely used in the evaluation of success of infrared RTI's, because the less colour information the more objective the comparison between visible RGB colour and monochrome infrared RTI's (Figure 277). The diffuse gain rendering mode successfully underlines details. It may result in totally unrealistic images, which resemble drawings rather than photographic documentation (Figure 278). The image unsharp masking is useful for the visualisation of low relief detail of manufacture evidence and damage. A characteristic example is its application for the visualization of striations in alabaster vessels and the textile imprints in metals (Figure 279). The coefficient unsharp masking is a very good condition reporting option as it emphasizes reflectivity discontinuities (Figure 280). The luminance unsharp masking is useful for condition reporting and stylistic examination of artefacts because it underlines depth discontinuities (Figure 281). Even in the case of infrared RTI, where the depth of the inner layers of artefacts are less obvious, luminance unsharp masking succeeds in visualizing depth variation. The normal unsharp masking emphasizes the geometry features and as a result it is valuable for the visualization of deformation and physical damage, such as pitted surfaces (Figure 282). The multi-light enhancement mode is useful for the visualization of vases and other artefacts types of complex geometry, where large portions of the artefact may be in shadow. But their most valuable contribution is in the visualization of the mounted papyrus, where the only

available light directions were extremely low, due to the presence of the mount (Figure 283).

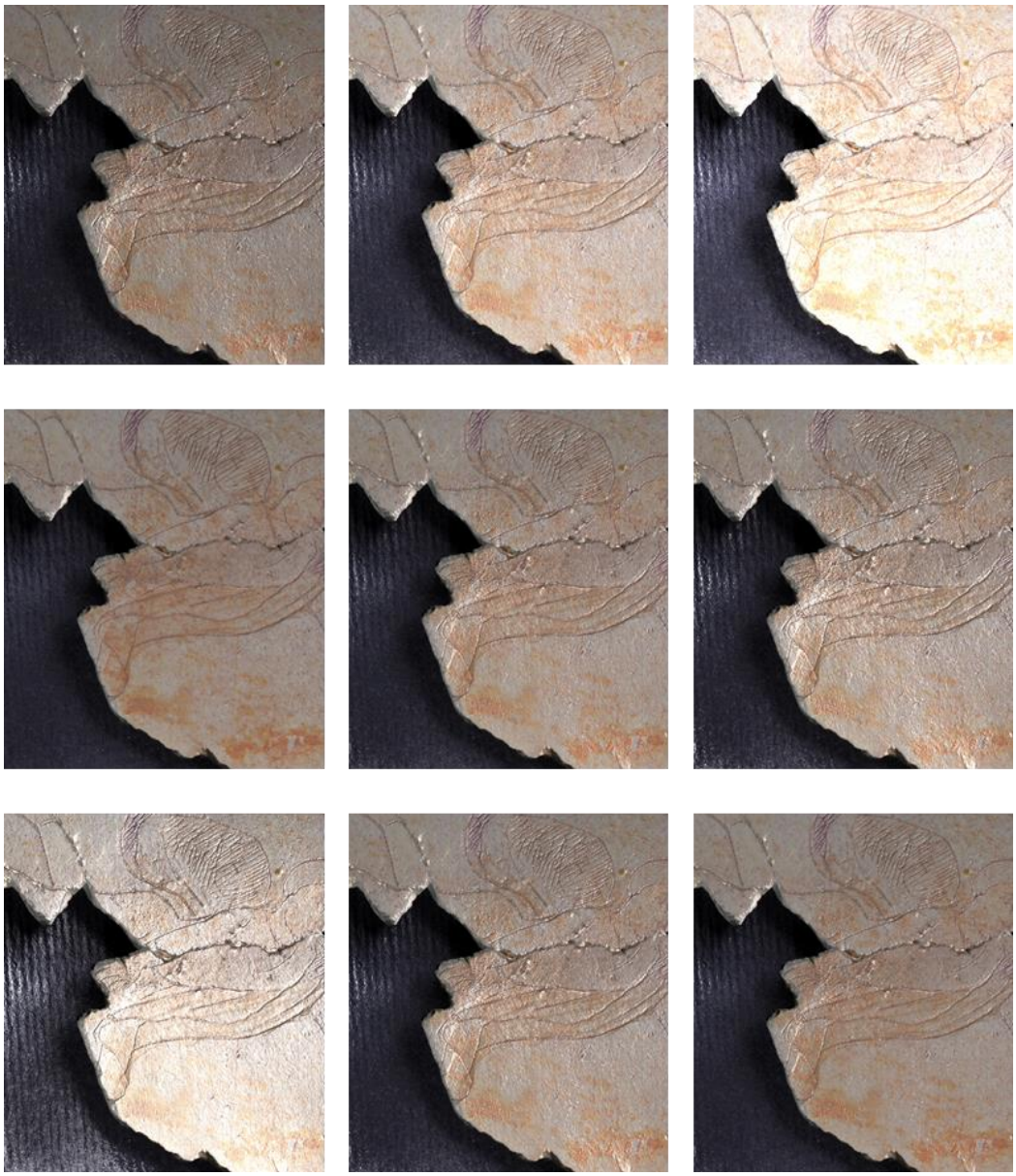


Figure 277: Incised ivory plaques visualised in RTI format in specular enhancement rendering mode. The value of the kd parameter is increasing from left to right (top), the value of the ks parameter is increasing from left to right (middle), the value of the N parameter is increasing from left to right (down) (Image author's own).

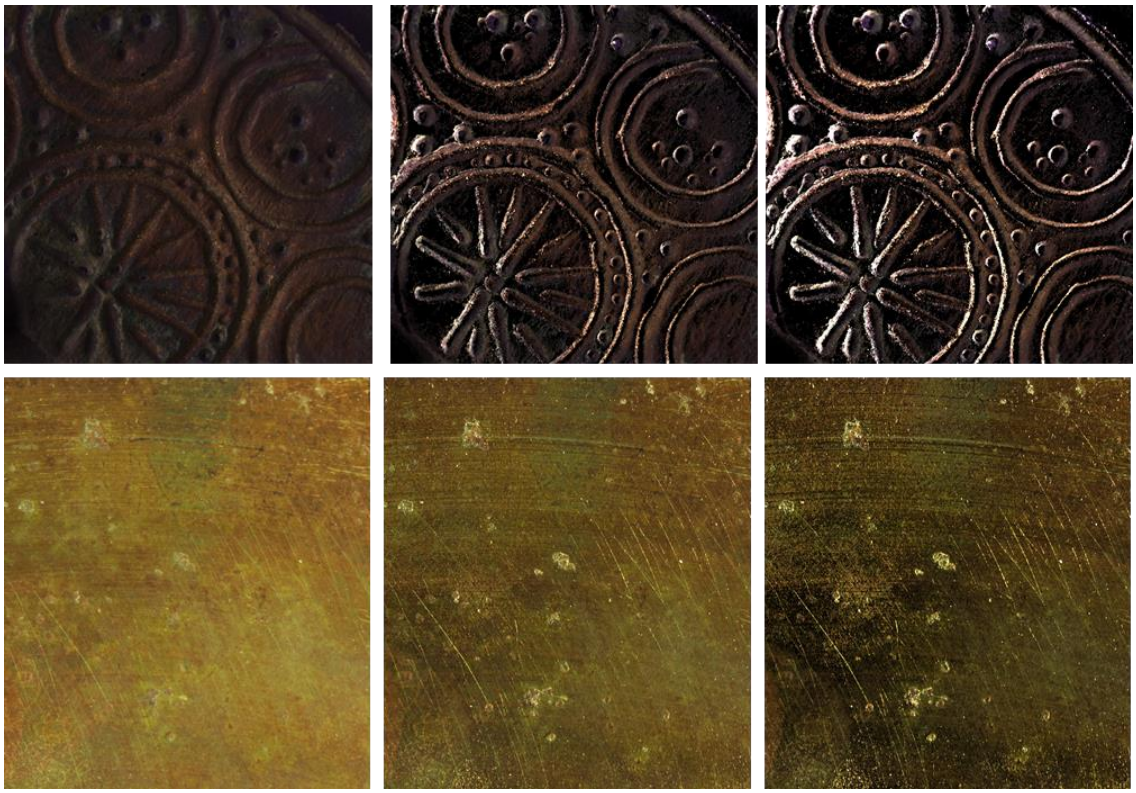


Figure 278: Silver discs and bronze mirror detail visualised in RTI format in diffuse gain rendering mode. The value of the parameter gain is increasing from left to right (Image author's own).

Figure 279: Alabaster alabastron visualised in RTI format in image unsharp masking rendering mode. The value of the parameter gain is increasing from left to right (Image author's own).

Figure 280: Red figure pelike H2, detail, visualised in RTI format in coefficient unsharp unsharp masking rendering mode. The value of the parameter gain is increasing from left to right. Infrared RTI 950nm (top), visible (down) (Image author's own).

Figure 281: Red figure pelike H2, detail, visualised in RTI format in luminance unsharp masking rendering mode. The value of the parameter gain is increasing from left to right. Infrared RTI 950nm (top), visible (down) (Image author's own).

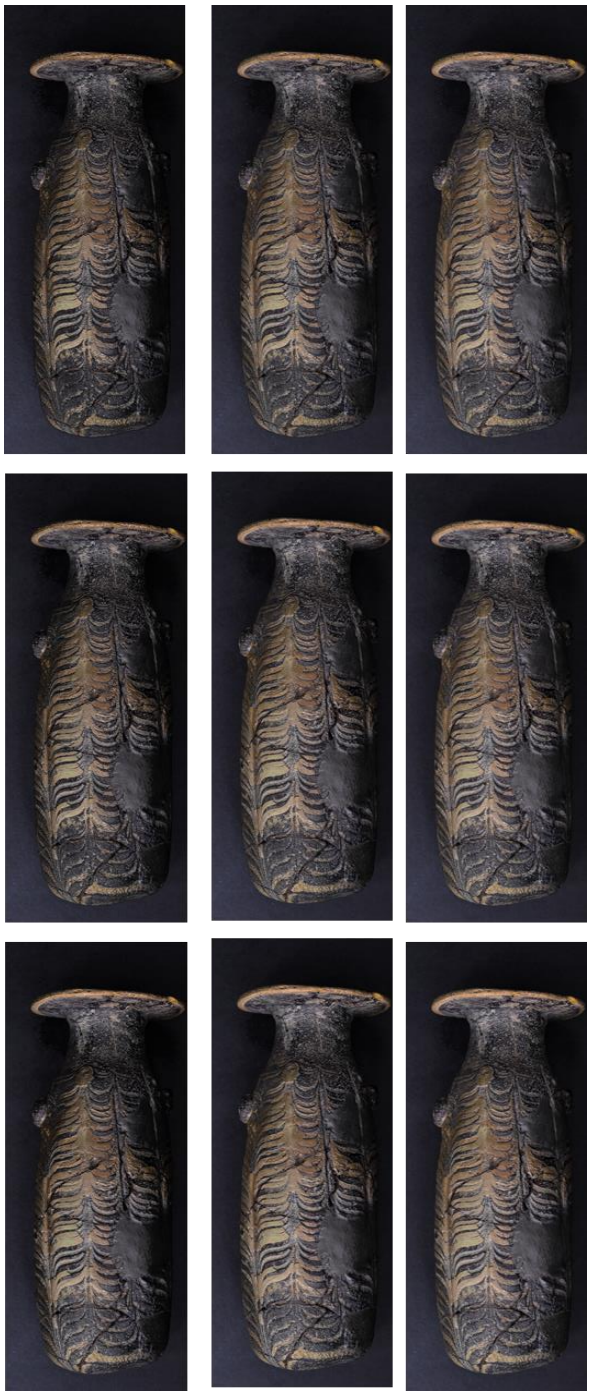


Figure 282: Glass alabastron visualised in RTI format in normal unsharp masking rendering mode. The value of the parameter gain is increasing from left to right. Environment 25% (top), 50% (middle) and 75% (down) (Image author's own).

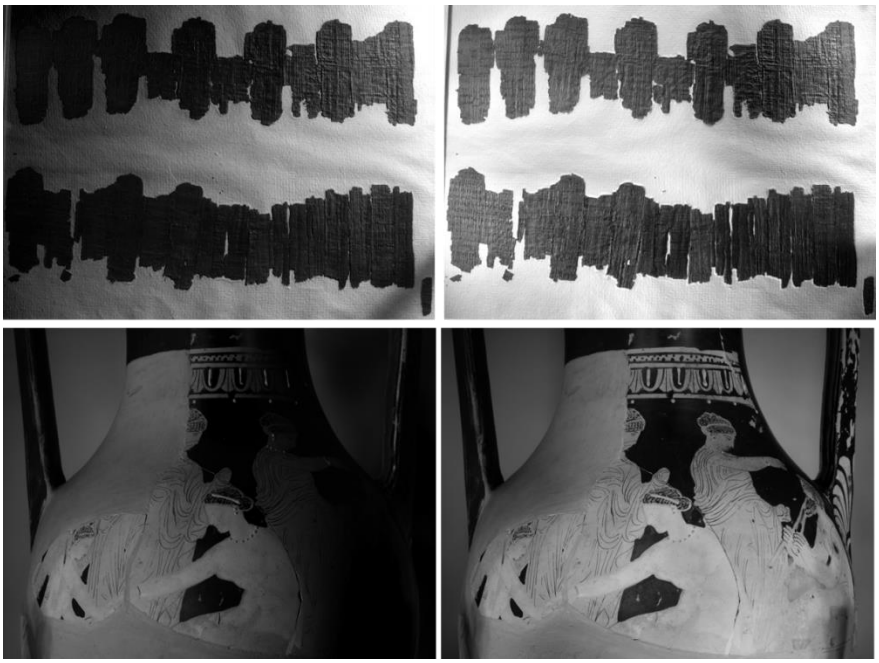


Figure 283: The Derveni papyrus fragment (top) and detail of the red figure pelike H2 (down) visualised in RTI format. Infrared RTI. Snapshots in default (left) and multi-light enhancement rendering mode (right) (Image author's own).

5.3.2.5 Digital image processing of RTI visualizations

Digital image processing of RTI visualizations can lead to useful illustrations that highlight specific features of the visualised objects. This experimentation was inspired by previous work on image processing (Brognara *et al.*, 2013; Raskar, 2004) mental ray contours (Earl *et al.*, 2011), maximum entropy calculation (Malzbender and Ordentlich, 2005), the CARE tool (see section 2.3.3.1.1 for a discussion) and normals based illustration (Toler-Franklin *et al.*, 2007).

In the coin example (Figure 284) the illustrations produced give a clear picture of the surface texture and may be useful for interpretation and presentation. Not only the legend appears even more discernible but also the surface anomalies due to corrosion is visualised too. The trace contour, find edges and the sketch filters are useful for the illustration of the legends and designs and surface texture (Figure 285). Find edges and trace contours filters produce similar effects by identifying transition areas. The difference is that find edges

in Photoshop emphasises edges with dark strong lines. The sketch filter resamples artistic sketching. For illustrations produced from coins RTI visualizations, the most useful features were the preservation of details and the adjustment of the thickness of the lines.

Figure 284: Coin, digital image (top left), normal map (top middle), trace contours filter (top right), emboss filter (below left) find edges filter (below middle) and sketch filter (below right) RTI visualizations processed in Photoshop (Image author's own).

Figure 285: Coin, detail, trace contours filter (left), sketch filter (middle) and find edges filter (right). RTI visualizations processed in Photoshop (Image author's own).

The trace contour filter creates visualizations that resemble contour maps by creating thin outlines in transition areas of brightness. Comparison of the same filtering approach applied to a digital image and RTI visualization in specular enhancement rendering mode demonstrates that the illustrations produced based on RTI are clear representations of the legend and the design (Figure 286). The value of filter parameter has an impact on the visualization produced. In case of lower values the legend and the design are more discernible, while increased value of the filter leads to the visualization of surface anomalies of lower relief detail. The former serves as a stylistic representation of the coin, while the latter is an illustrative representation of the coin's surface including not only features useful for identification and dating but also features useful for the characterization of the corrosion and conservation state.

Figure 286: Applying trace contours fitter to a digital image of a coin (up) and an RTI visualization in specular enhancement rendering mode (below). The value of the filter is increasing from left to right. Processed in Photoshop (Image author's own).

The illustrative visualization of surface anomalies due to corrosion is shown in Figure 287, in the comparison of the visualization produced from the application of trace contours filter before and after cleaning. The former demonstrates the visualization of depositions, encrustations and other surface anomalies due to corrosion with lines, covering almost the whole surface of the coin.

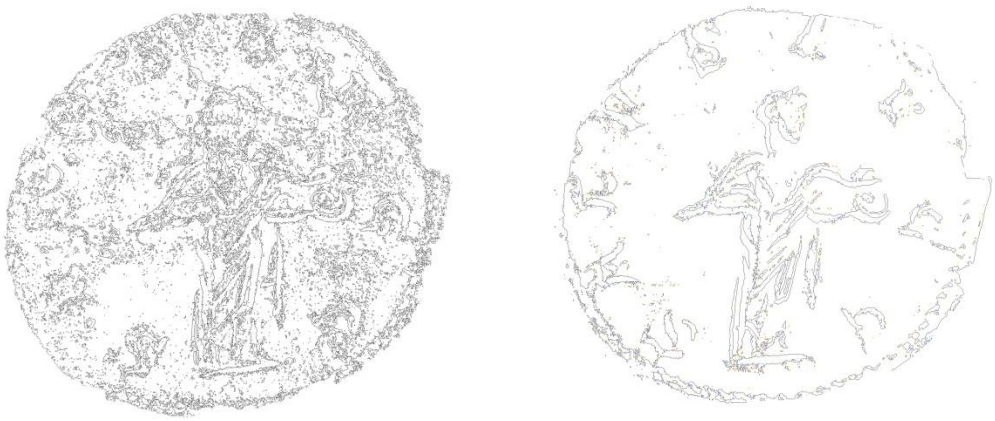


Figure 287: Coin, illustration produced by applying trace contour filter before (left) and after cleaning (right). RTI visualizations processed in Photoshop (Image author's own).

Find edges and trace contour filters proved to be a useful tools for the clearer identification of differences between digital images and RTI visualization. For example as discussed in section 5.3.2.2.4 in case of Faenza maiolica fragments RTI renderings reveal the craqueleure. Comparison of visualizations produced by applying the find edges filter in digital image and RTI visualization emphasizes the network of cracks (Figure 288). Also filtering RTI visualizations in the visible and infrared spectral area assists the comparative analysis of the artwork. For example the texture of the substrate in the IR RTI visualization after applying find edge and trace contours filters is emphasized by the horizontal lines as opposed to the smooth texture in the visible visualization. Using the same methodology different visualizations can be produced (Figure 289). In addition, this stylistic representation can be used for the demonstration of visual analysis results because of their efficiency in

emphasizing details. A characteristic example is the UV induced visible fluorescence RTI visualization of the skyphos, shown in Figure 290. The application of find edges filter results in outlines of the remnants of the conservation materials. These examples demonstrate that the subtractive illustration approach may be useful for interpretation and explanation of the results of multispectral RTI. Via blending and superimposing the filtered data with the normal RTI snapshot an illustration, stylistic representation of the object can be produced (Figure 291-292).

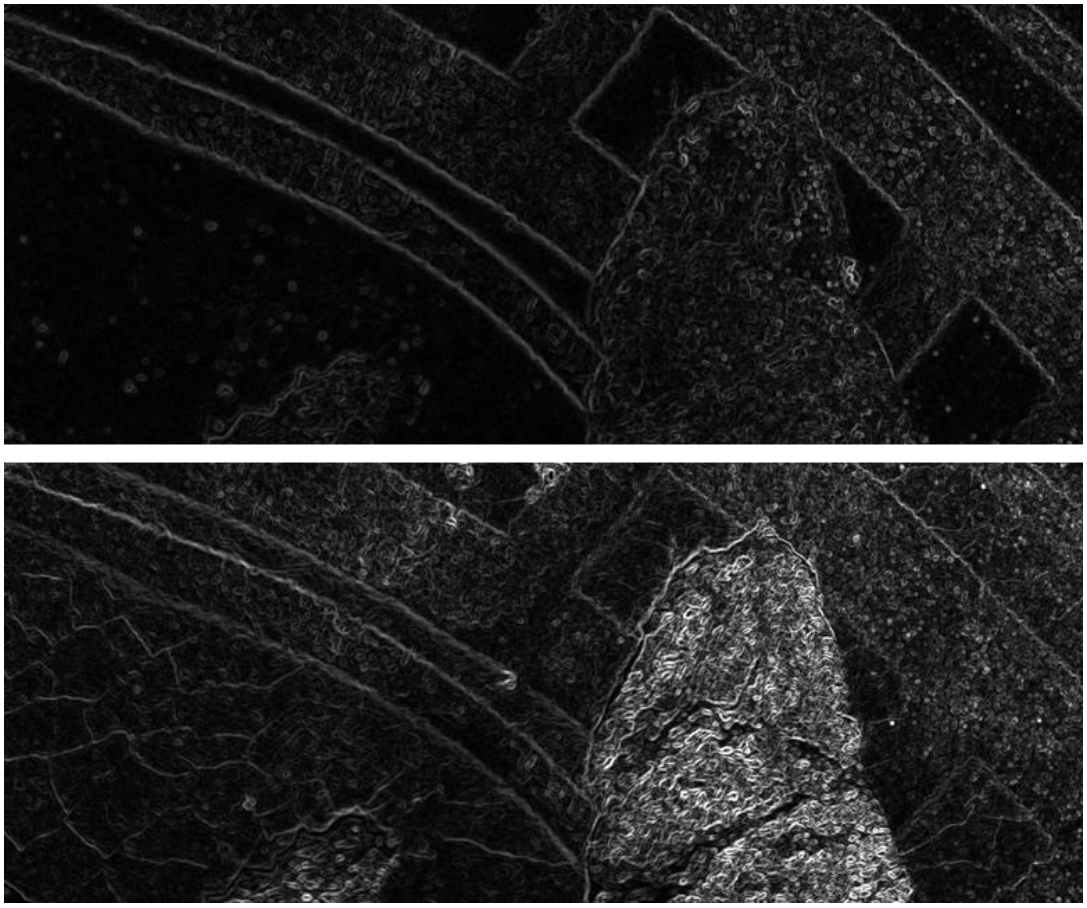


Figure 288: Detail of Faenza maiolica fragment. Application of the find edges filter to digital image (top) and RTI visualization (below). Processed in ImageJ (Image author's own).

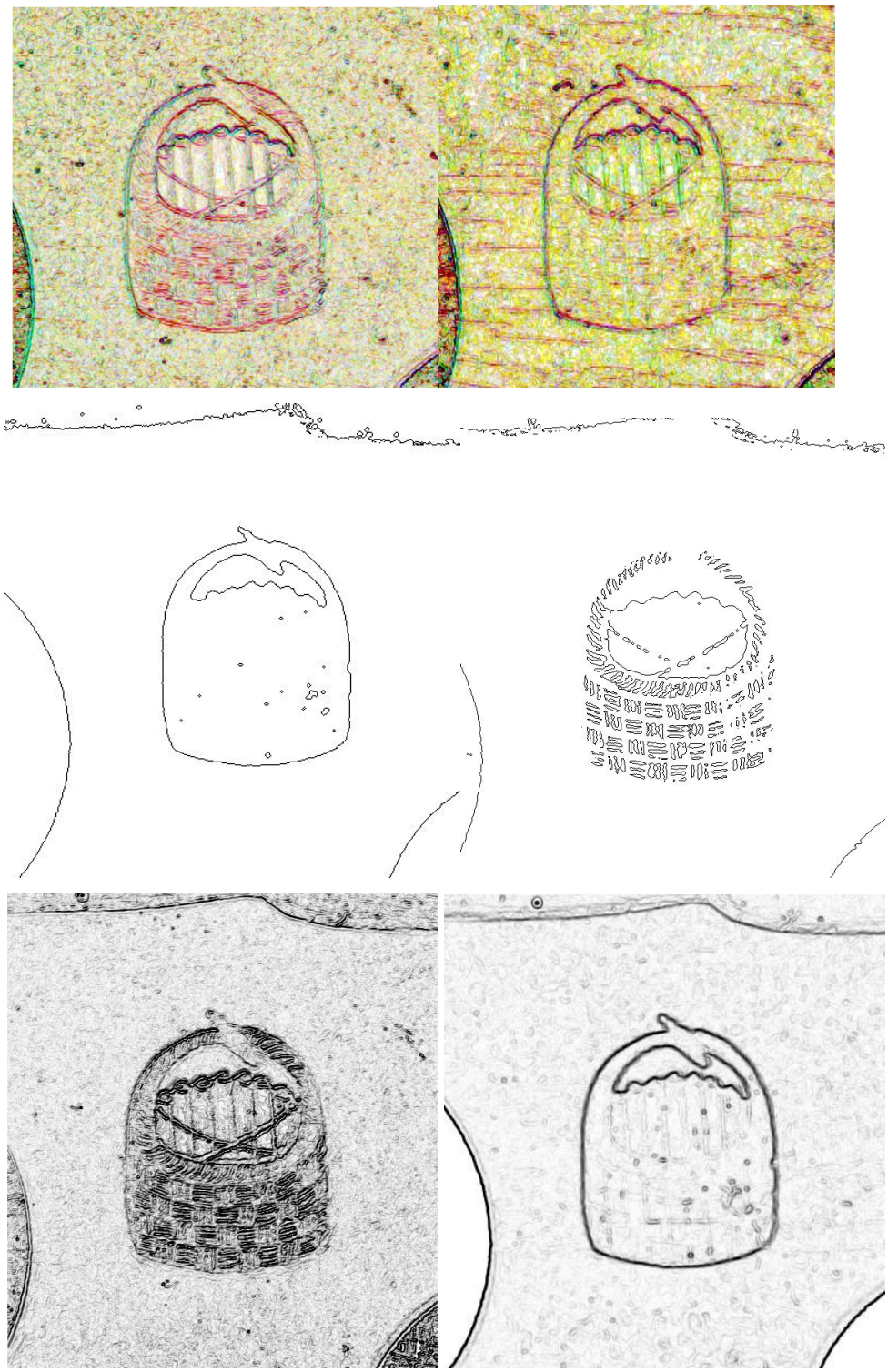


Figure 289: Icon, visible (left) and IR (right). Applying find edge and trace contours filters to normal maps and RTI visualizations (Image author's own).

Figure 290: Gnathian skyphos, detai. find edges filter Application of the find edges filter to digital image (left) and UV-RTI visualization (right). Processed in ImageJ (Image author's own).

Figure 291: Silver disc, RTI Visualization (top) and blending RTI visualization with filtered image (right) (Image author's own).

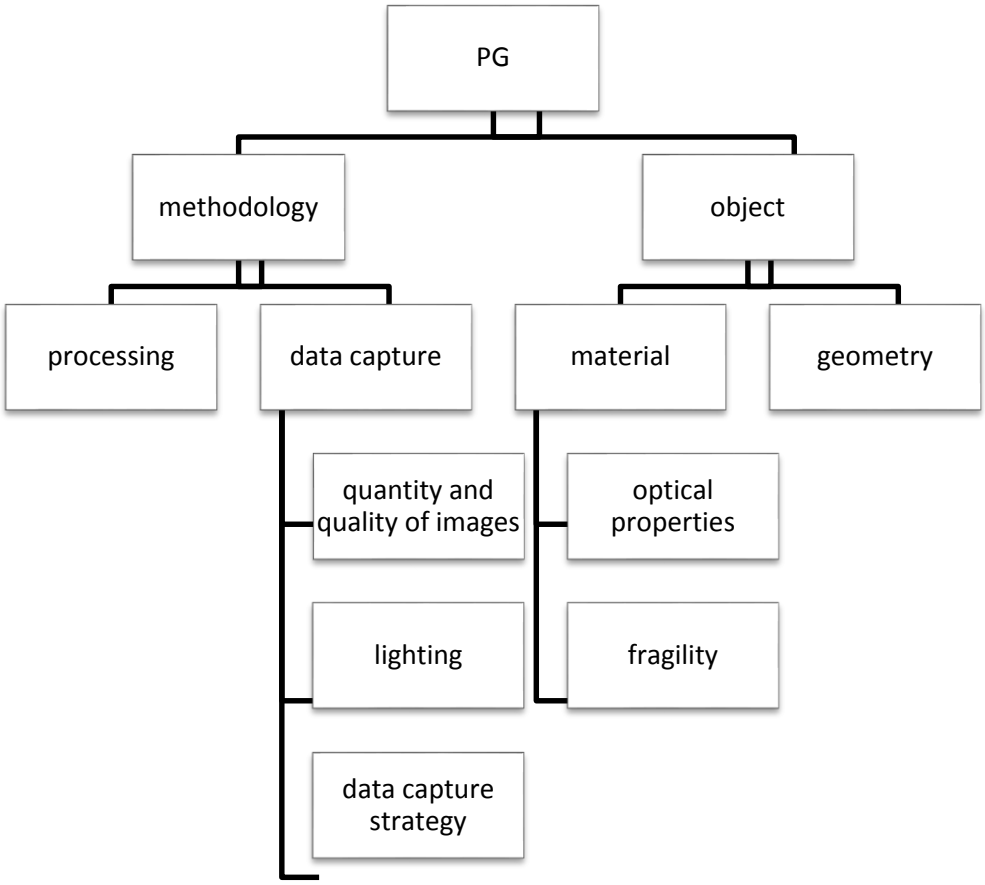
Figure 292: Derveni Papyrus fragment, detail. RTI Visualization, filtered images and image overlay of filtered images (clockwise from top left).

The already presented examples lead to the conclusion that filtering RTI visualizations may be useful for documentation, analysis and demonstration purposes. There is a clear need of meticulous documentation of the processing filters applied to each illustration produced. The development of an improved version of RTI Viewer, with which will incorporate standard image processing filters will provide assistance in documentation of filtering and will provide an easy way to produce not only RTI visualizations but also stylistic illustrations of artefacts. At the same time the incorporation of filtering option to viewers in addition to further experimentation will enable the development of guidelines so as to avoid confusing illustrations.

5.4 PG

5.4.1 Visualization methodology

The quality of the photogrammetric reconstruction depends on methodology in relation to the characteristics of the object; including its surface properties, geometry and conservation state (Graph 32). The key elements of the methodology are the data capture and processing. These parameters will be analysed in the following sections.



Graph 32: Parameters that influence the PG reconstruction (Graph author's own).

5.4.1.1 Data capture

5.4.1.1.1 Data capture strategies

Two different data capture strategies were employed. The first one (method 1-Figure 293) follows the recommendations of photogrammetric software, as the object is static, positioned on a table and the camera is moving around the object, capturing images from different angles which create a virtual hemisphere. For the second methodology (method 2-Figure 294) the object is moving, following a rotation movement around its vertical axis and the camera is static. After a complete rotation the camera is positioned on an angle and the object is again moving around its axis.

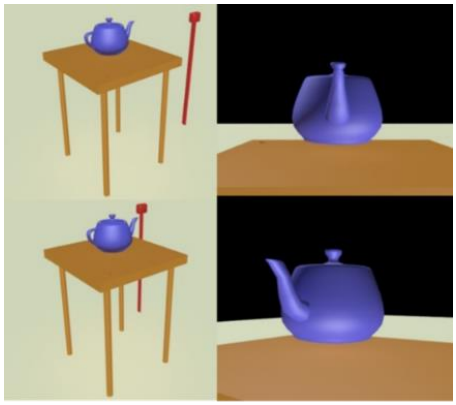


Figure 293: Schematic representation of method 1. The camera is moving around the object resulting in two different views of artefact (Image author's own).

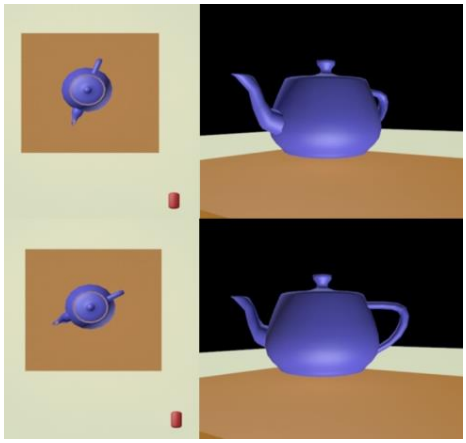
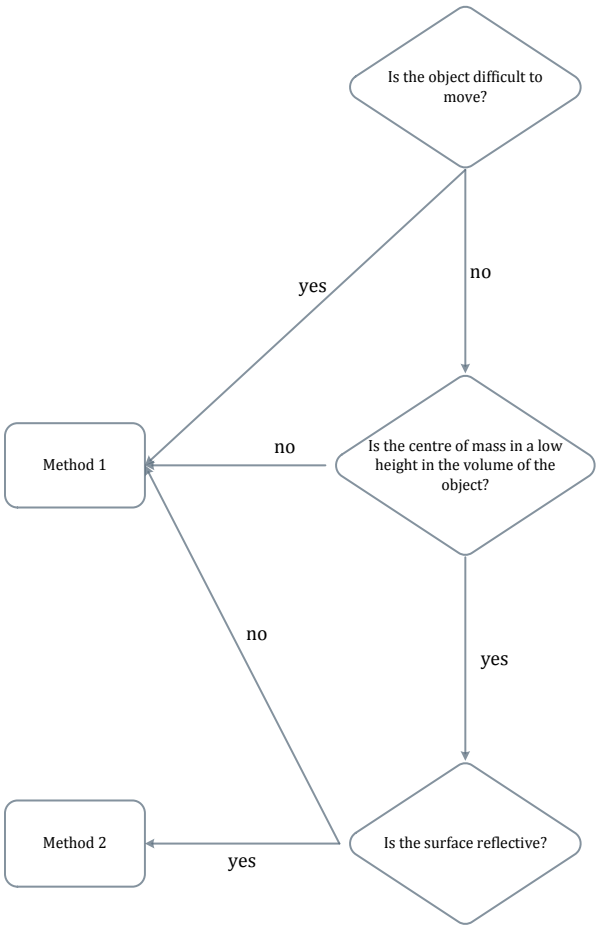


Figure 294: Schematic representation of method 2. The camera is static and the object is moving around its axis (Image author's own).

Method 2 is an easier and faster data capture approach but it is not feasible in all objects. Method 2 is proposed in the case of materials that can be moved or rotated easily and with safety, meaning not extremely fragile and with a centre of mass at a relatively low height. It is highly recommended in case of reflective objects, as the option to perform capture in a controlled environment provides a high quality dataset. Method 1 is recommended in case of materials that cannot be moved or rotated easily, such as very large or fragile objects.

Graph 33 presents a flow chart for choosing the appropriate data capture strategy based on the already mentioned criteria, mainly the size, fragility and optical properties of the object.



Graph 33: Flowchart for choosing the appropriate methodology for PG based on objects properties (Graph author's own)

In order to capture the base of the object all the images can be processed together in the photogrammetric software. The base of the object can be captured by position it upside down (method 2-a). A compromise is to turn the object on its side and place it on a foam stand in order to support the object (method 2-b) (Figure 295). One should take in to consideration the geometric complexity of each object, in order to decide the capture strategy. Table 13 recommends the most appropriate data strategy for common vessel shapes.

Figure 295: Data capture of an amphora fragment following method 2-a (top) and 2-b (below) (Image author's own).

Table 13: Recommendations for choosing the appropriate methodology based on most common shapes of vessels and vases.

Method 1	Method2-a	Method2-b
Large vessels (e.g. amphoras) Lebes gamikos Loutrophoros	Stamnos Bell, column and calyx crater Skyphos Kantharos Phiale Plate Lekanis Pyxis (opened)	Pelike Hydriai Volume Krater Oinochoe Choes Lekythos Alabastron Askos Pyxis (closed) Phyton

Two datasets, quantitatively and qualitatively similar, were captured following methods 1 and 2. After image alignment in Agisoft photoscan the camera distribution for method 2 is more structured (Figure 296). Method 1 results in a lower quality reconstruction, as it fails to visualize the surface texture. For example, in the front side of the vessel model 1, the texture appears too rough, while on the bottom the labels are not visible (Figures 297-298).

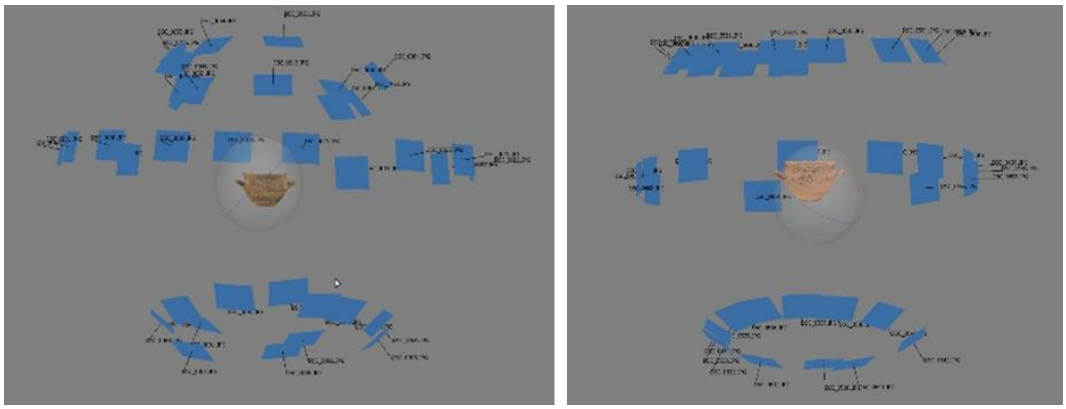


Figure 296: Camera distribution for mehod 1 (left) and method 2 (right) (Image author's own).

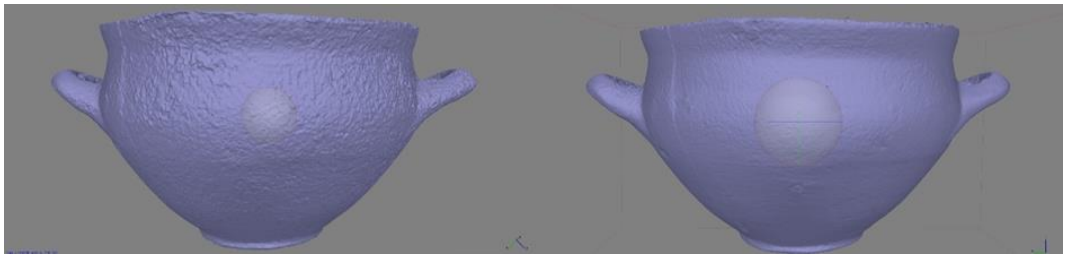


Figure 297: Comparison of method 1 (left) and method 2 (right) reconstructions, front side of the vessel (Image author's own).

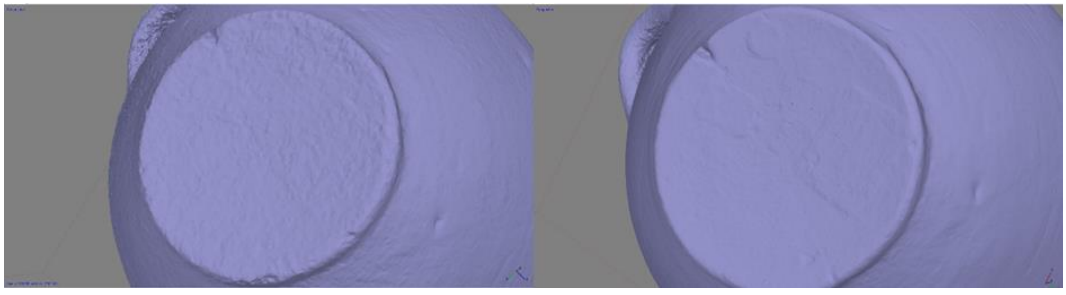


Figure 298: Comparison of method 1 (left) and method 2 (right) reconstructions. Base of the vessel (Image author's own).

5.4.1.1.2 Lighting

Lighting is a crucial parameter in photogrammetry, and capturing images in a controlled lighting environment is preferred. Sudden changes in lighting between captures diminish the quality of the model. This is of great significance in case of reflective materials, such as glazed ceramic surfaces, because the reflections on the black glaze on the images results in unacceptable models, particularly in terms of geometry. Among the most common problems are the creation of models with large holes and unrealistic texture.

Gnathian pottery is a characteristic style which presents a reflective appearance because of the presence of black glaze. Gnathia pottery, named after the large quantities of it found in Egrazia, Apulia, Southern Italy, during the late fourth to the early third century BC, has a distinctive decoration pattern with geometric and floral motifs (vine pattern) including grapes, leaves, and tendrils produced by added colour over the black glaze, and sometimes incisions.

A Corinthian-type gnathian skyphos, a deep bodied drinking cup with a plain rim, low foot and two horizontal handles below the rim, was used as a case study. On one side there is a band of white egg-pattern on the rim, and below this is a band of wavy lines also in white, a row of white dots and a red stem followed by a highly stylized grapevine pattern. The back side features a single white wreath with an incised stem. It belongs to the middle-late Gnathian style. It might be work of the Knudsen group because of its shape and decoration scheme. The absence of tendrils and leaves from the upper side of the red stem, as well as the total separation of the vine and the stem, are characteristic of the work of Knudsen group according to Green (2001).

The skyphos was captured using method 2 with and without a soft box. Both datasets were processed using the same settings. Comparison of models captured with and without the soft box reveals that the former is a better method in for reflective materials. In the resulting model without soft box the details from the painted and incised decoration on the upper body, close to the rim, are not visualised, the texture appears rough and unrealistic and there are areas with holes on the lower part of the body. However, geometry and surface

detail decoration features are visible in the model, when a soft box was used (Figure 299).

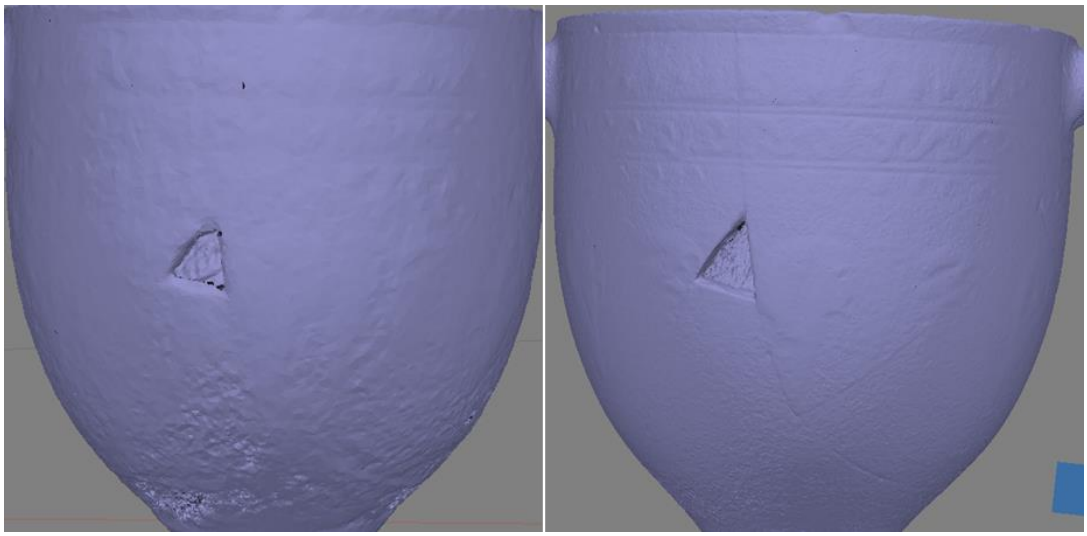


Figure 299: Ganthian skyphos, detail, renderings from PG models created following method 2 with (right) and without (left) soft box (Image author's own).

5.4.1.1.3 Microscopic PG

The data capture is based on the methodologies described in the previous section. In case of normal microscopes equipped with a camera only method 2 can be used. This requires handling of the object under the microscope lenses, which is difficult in practical terms because of the small size. Moreover, it is highly likely for the samples to be fragile and not able to withstand such manipulation. In order to overcome the already mentioned disadvantage of normal microscopes, the use of USB microscopes is recommended. A set of images can be captured by simply moving the USB microscope around the area to be captured. This is a demanding process because some camera positions may be overlooked and images may be blurry due to the manual movement. USB microscopes equipped with touch sensitive buttons can be useful. Preferably the microscope can be attached to a stand with vertical and horizontal adjustment and rotation capability. The AM211 Dino-Lite USB microscope has been used for testing this methodology, as well as a backlight pad and a stand (Figure 300). Modern versions of USB microscopes include useful features for microscopic photogrammetry, such as the adjustable polarization for suppressing glare from reflective materials and switchable LED

lights, and come with resolution of up to 5 megapixel and magnification of up to 500x magnification.

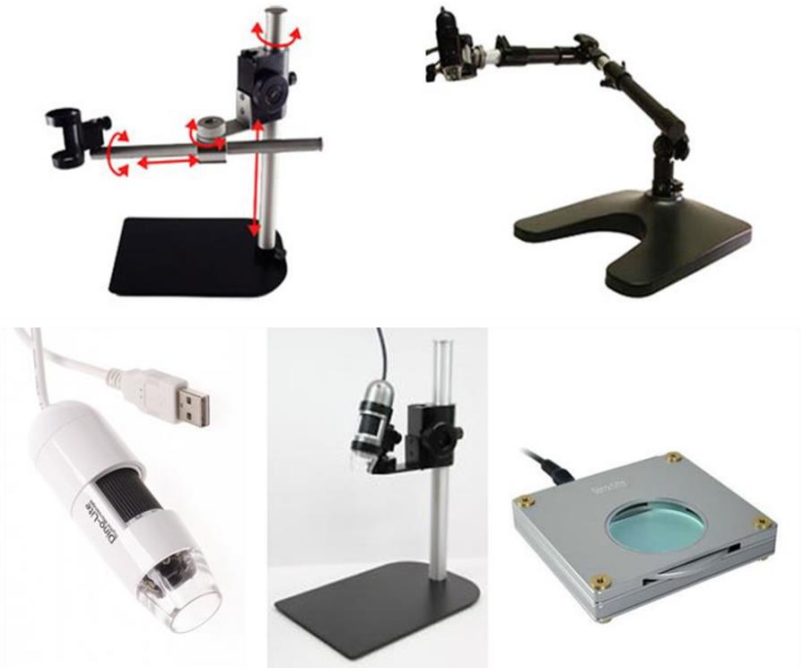


Figure 300: USB microscope stands for easy micro PG data capture (top). USB microscope, stand and light pad used (below) Available from: http://www.dino-lite.com/web/index.html

5.4.1.1.4 Multispectral PG

Multispectral photogrammetry combines the ability of multispectral imaging to reveal features beyond the visible with the 3d modelling capabilities of photogrammetry. Data capture can be completed using a modified UV-VIS-IR dslr camera, adequate filters and radiation sources.

5.4.1.1.5 Transmitted PG

Transmitted photogrammetry combines the results of trans illumination and trans irradiation with the 3d modelling capabilities of photogrammetry. For trans illumination data capture, the object is placed on a light table and the acquisition can be completed following the basic methodology.

5.4.1.2 Processing

5.4.1.2.1 Pre-processing

Features depicted in the background of the images are processed while the point cloud is being built. Although these features can be subtracted from the model during processing in Agisoft photoscan software using masks, pre-processing of images and in particular removing the background of images using appropriate software (e.g. Photoshop, Corel etc.) is recommended. This pre-processing facilitates easier use of masks at a later stage of processing because the user can select the areas easily. Sometimes after pre-processing the use of masks becomes unnecessary. Models created without pre-processing of images require post processing. This procedure is laborious and the precise deletion of unnecessary data is difficult.

5.4.1.2.2 General workflow

Images are aligned based on common points found on images. A sparse point cloud and the camera positions are computed. The user can inspect the distribution of images around the object. In case of incorrect alignment the user can choose to realign the photos, indicating a set of correctly aligned images. The next step is the computation of the dense point cloud and the reconstruction of the geometry. Finally, texture is built and the object is ready to be exported or viewed (Figure 301). The process of PG reconstruction is represented in Graph 34.

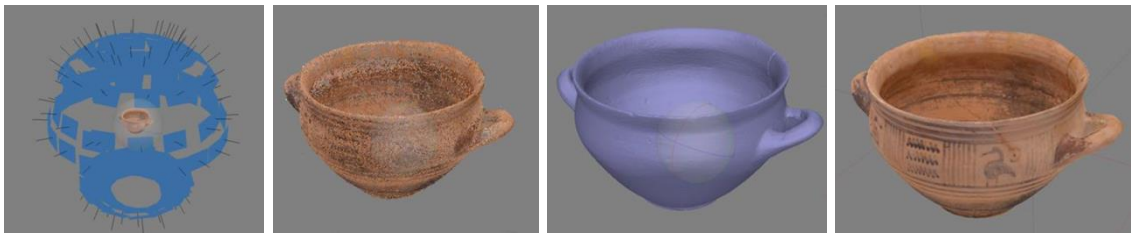
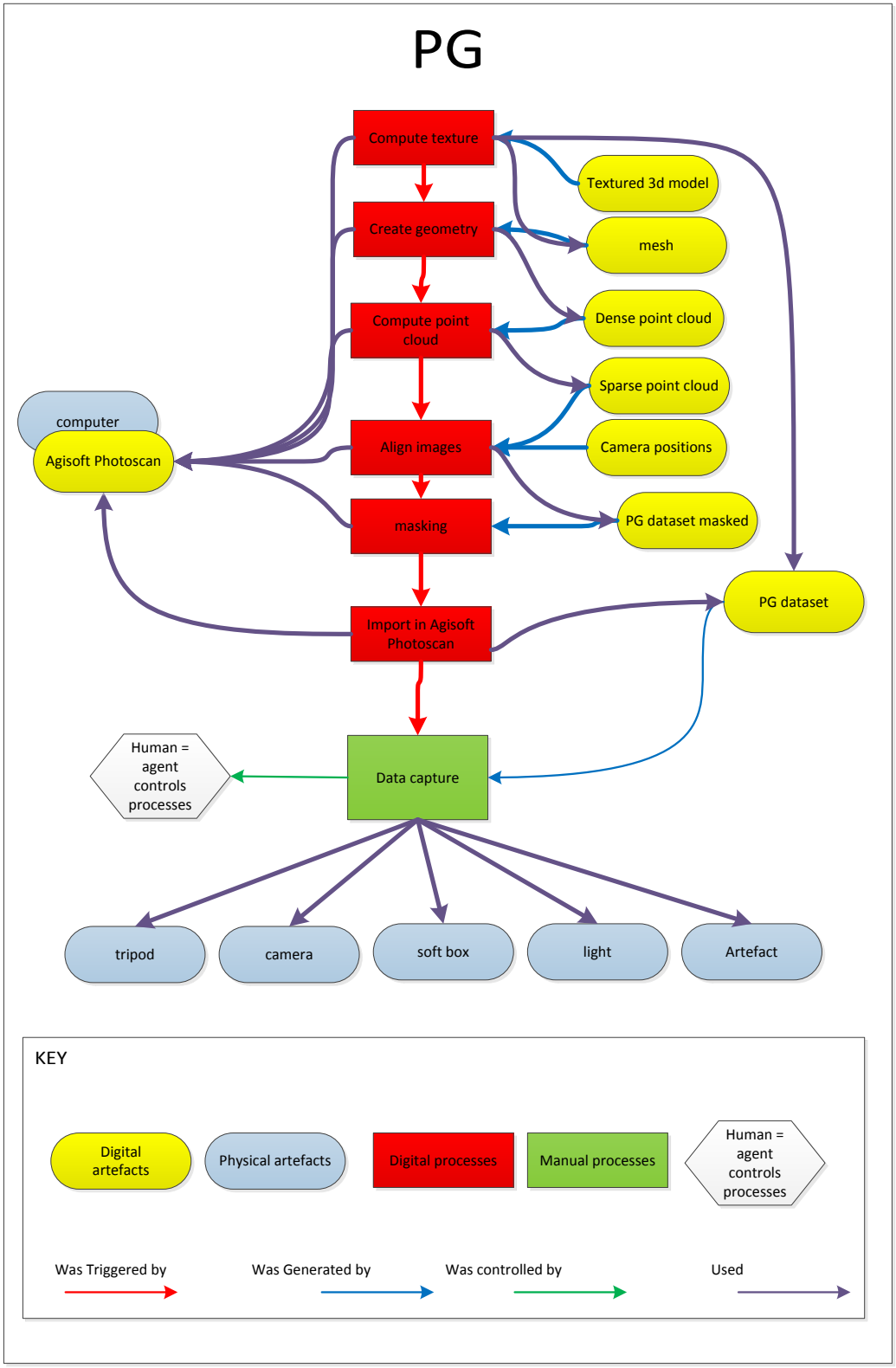


Figure 301: 3d reconstruction workflow (Image author's own).



Graph 34: Open Provenance Graph for PG (Graph author's own).

5.4.1.2.3 Impact of processing quality and number of images

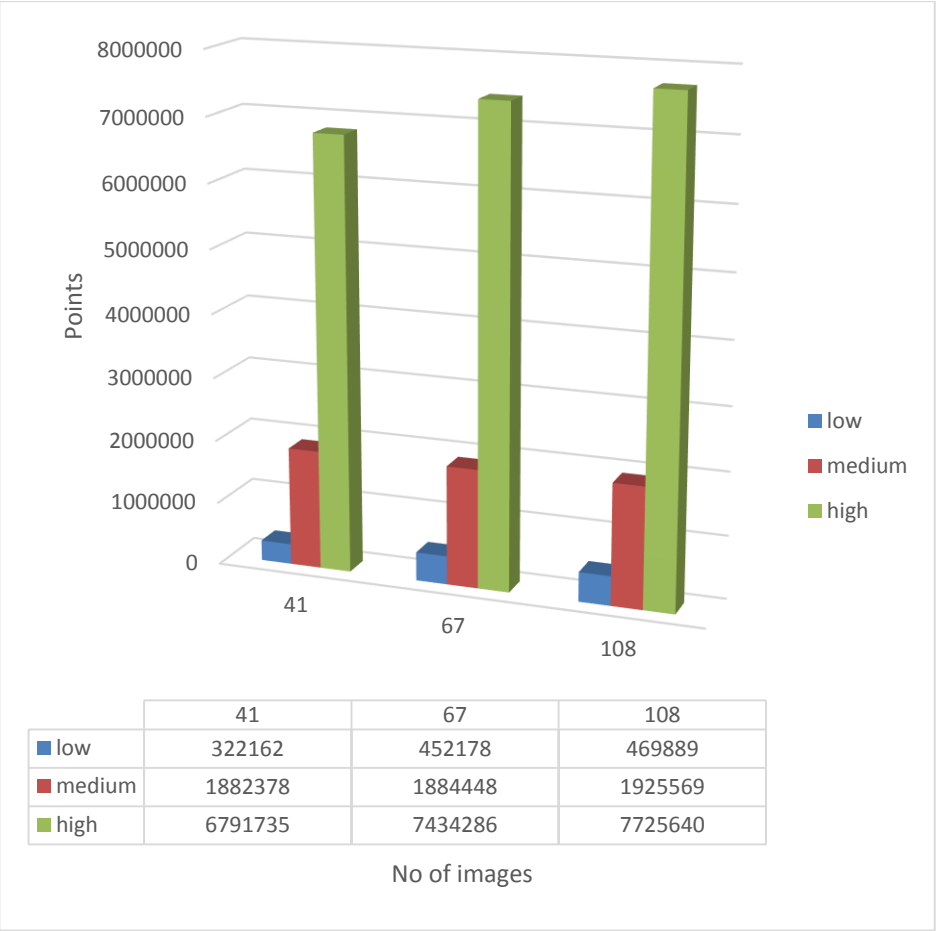
Nine reconstructions were created for the kantharos at different processing settings (low, medium, high) and with different number of input images (41, 67 and 108 images)[55]. Red colour was used for the renderings of low quantity datasets, green for medium quantity and blue for large datasets. Darker colours were used for high quality processing, lighter tones for medium quality and pale tones for low quality (Table 14). As expected, the quality of the model is enhanced with the ascending number of images and the use of high quality settings in processing. As shown in Graph 35, the use of high quality settings has a tremendous impact on the point cloud of the reconstructed model. The use of high quality settings tends to reconstruct point clouds up to 4 times more dense than medium quality settings.

Although these findings were expected based on software recommendations and previous work, no attempt has been made so far towards the evaluation of photogrammetic reconstruction for conservation purposes.

Table 14: Number of images, quality settings and colour coding for the PG reconstructed 9 models.

Model No	No of images	Quality	Pseudo-colour in NPR renderings
1	41	low	
4		Medium	
7		High	
2	67	low	
5		Medium	
8		High	
3	108	low	
6		Medium	
9		High	

[55] See Digital Library, folder section 5.4, files USOU-UK-CER-KA_high settings_41 images.psz, USOU-UK-CER-KA_high settings_67 images.psz, USOU-UK-CER-KA_high settings_108 images.psz, USOU-UK-CER-KA_low settings_41 images.psz, USOU-UK-CER-KA_low settings_67 images.psz, USOU-UK-CER-KA_low settings_108 images.psz, USOU-UK-CER-KA_medium settings_41 images.psz, USOU-UK-CER-KA_medium settings_67 images.psz, USOU-UK-CER-KA_medium settings_108 images.psz



	41	67	108
low	322162	452178	469889
medium	1882378	1884448	1925569
high	6791735	7434286	7725640

Graph 35: The point cloud density of the nine models reconstructed at low, medium and high quality settings with datasets of 41, 67 and 108 images (Graph author's own).

All datasets were aligned correctly, apart from a dataset of a limited number of images processed at low quality settings (model 1). The geometry was poorly represented in low quality models (models 2 and 3). For example, the chip missing from the base is not visible and the handle is not reconstructed accurately. Only an indication of the join which goes vertically down the rim is observable. In medium quality settings the representation of the geometry was acceptable but fine surface topography is not visualised (models 4-6). When high quality settings were used the texture can be reconstructed even with a limited number of images (model 7). Of course the use of complete datasets provides the opportunity to detect minor details (models 8-9). From visual comparison there are slight differences between the model reconstructed from 67 and 41 images in medium quality settings (model 5 and 6). Also the models

of 67 and 41 images at high quality settings are quite similar (model 8 and 9) (Figure 302-Figure 304).

Figure 302: The nine models, renderings in 3ds max, top views. The colour key is presented in Table 2 (Image author's own).

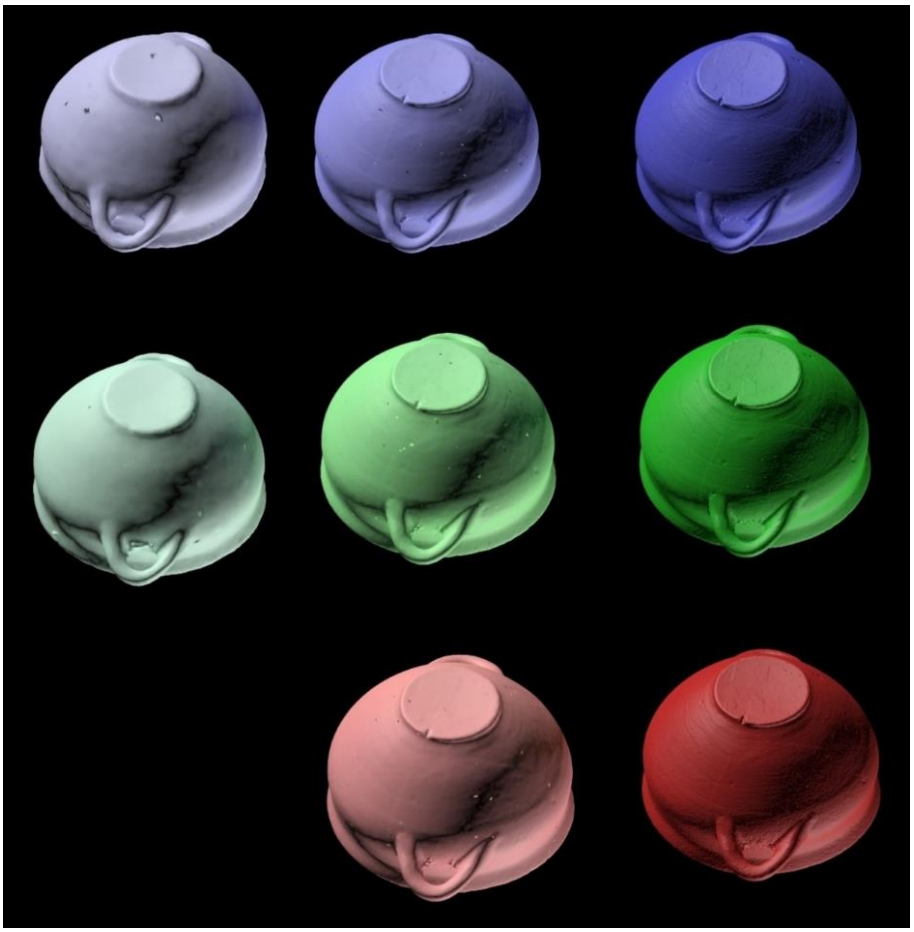


Figure 303: The nine models, renderings in 3ds max, bottom views. The colour key is presented in Table 2 (Image author's own).

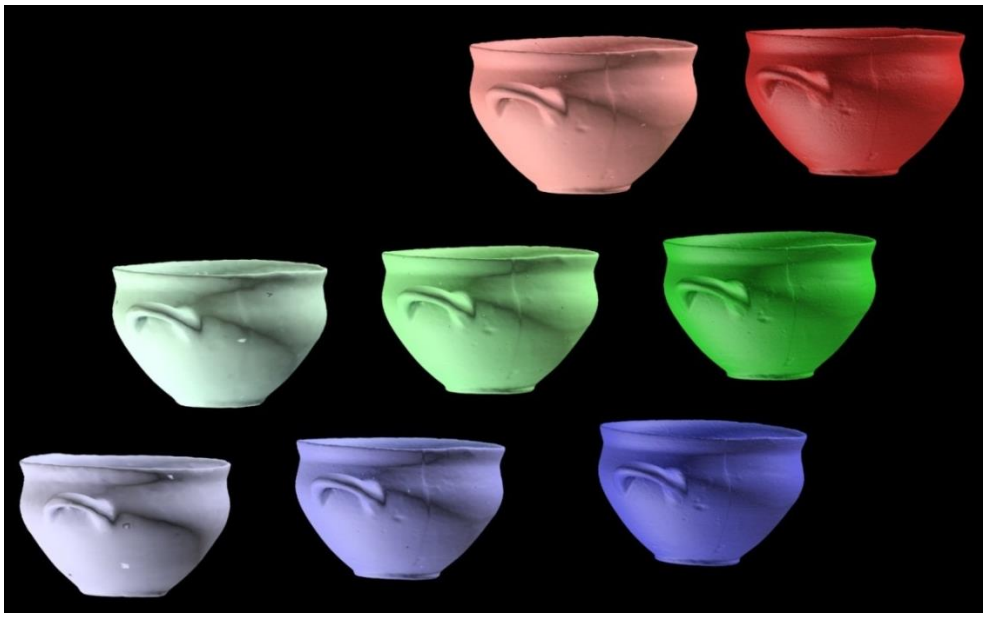


Figure 304: The nine models, renderings in 3ds max, side views. The colour key is presented in Table 2 (Image author's own).

In general high quality models provide a clear representation of surface shape and texture. They are useful for conservation documentation, examination and monitoring purposes, when the visualization of detail is of great importance. When this kind of visualization is not considered necessary and a simple representation of the geometry of the vessel is adequate, such as shape based typology studies, medium quality settings can be used for the reconstruction, so as to save processing time, computational power and storage. These are general purpose models useful for archaeological visualization and dissemination. Finally, models reconstructed at low quality settings are of limited use in the archaeology and cultural heritage sector.

5.4.1.2.4 Texture generation

Four main options are available for texture mapping; generic, orthophoto (texture generation based on orthographic projection), single photo (texture generation based on one photo) and keep uv (texture generation based on current parameterization). Apart from the texture generation parameters already discussed, Agisoft software provides the opportunity to choose from a list of different blending modes of the images for the generation of the texture atlas, such as mosaic, average , min and max intensity and spherical. In the Mosaic mode the software uses the most appropriate photo for texture

mapping while in the Average mode it uses the average value of all pixels from individual photos. In mix and max intensity the pixels of minimum and maximum intensity are selected respectively. In the spherical mode the software maps the texture assuming that the object has a spherical shape.

Single and keep uv texture mapping options result in problematic and incomplete texture generation and are therefore inappropriate. Generic and orthophoto provide a complete texture mapping, with the former considered the most appropriate for ceramics, because of their circular shape. Comparative examination of generic and orthophoto texture generation of an incomplete medieval jug from Southampton demonstrates that the former is a better approach, and reveals the problems occurred due to orthographic projection on the ceramic. In particular false texture was generated for the interior and the base of the vessel (Figure 305). Experimentation reveals that the best option for blending was the mosaic and the average mode. Although there are slight differences, the former proved to be the most accurate option for blending mode (Figure 306). Spherical, min and max intensity lead to unacceptable results (Figure 307-Figure 308).

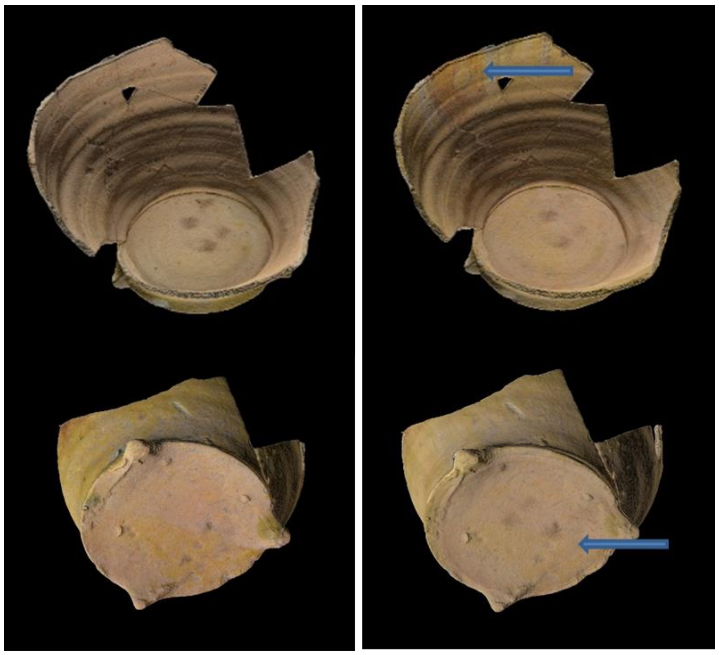


Figure 305: comparison of generic left and orthophoto right. In the orthophoto false texture generation is evident in the interior (1) and the base (2) of the vessel (Image author's own).

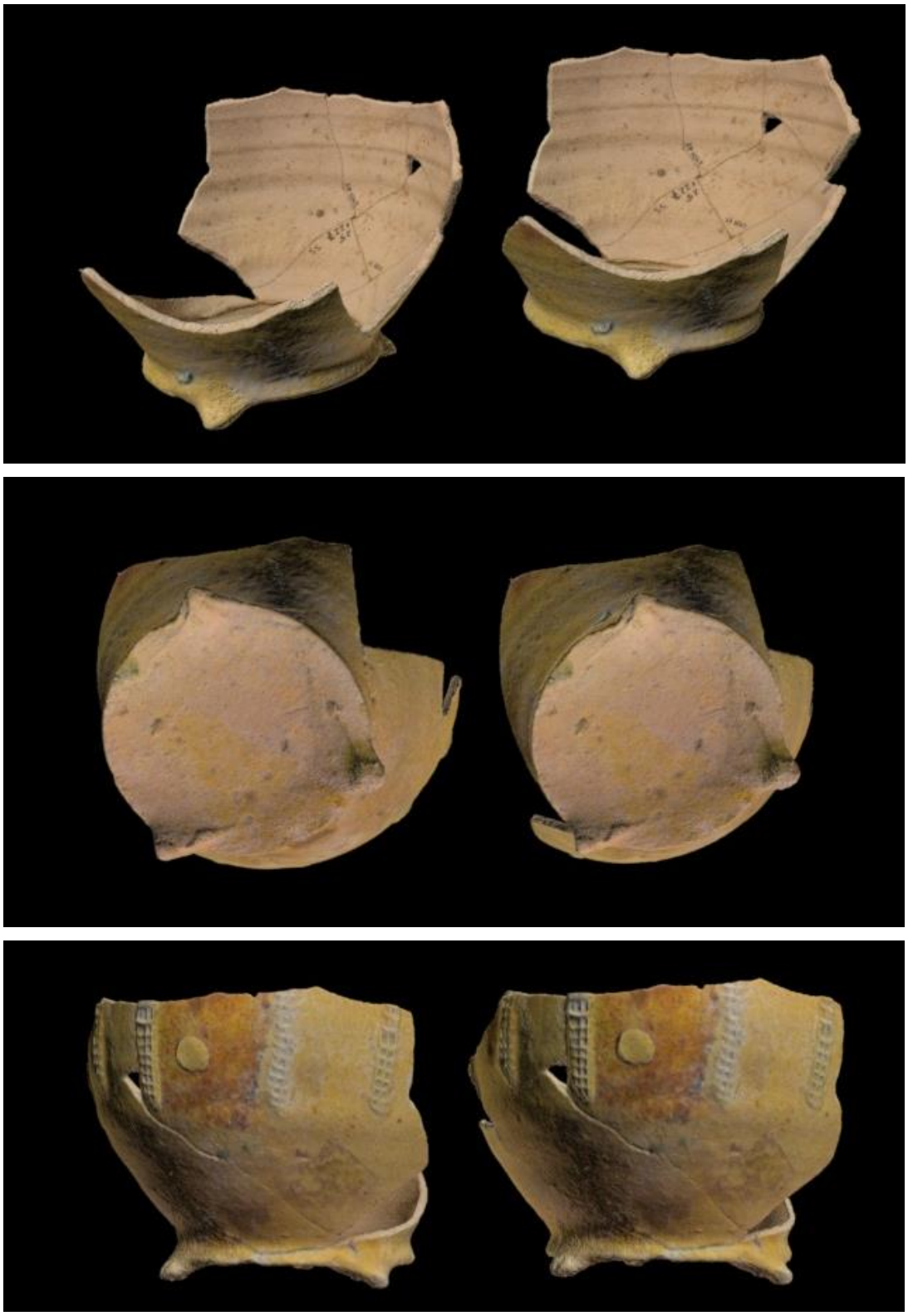


Figure 306: Rendering in 3ds max of incomplete medieval jug with generic average (left) and mosaic (right) blending mode (Image author's own).

Figure 307: Rendering in 3ds max of incomplete medieval jug with generic spherical texture generation. Arrow indicates area of false texture generation (Image author's own).

Figure 308: Rendering in 3ds max of incomplete medieval jug with max (left) min (right) intensity. Unrealistic colour visualization (Image author's own).

5.4.2 Results and discussion[56]

5.4.2.1 Paintings

A canvas tester used as a case study for RTI experimentations (section 5.3.2.1.2) was used for the experimentation on PG. The, normal, infrared, trans illumination, trans irradiation and microscopic PG methodologies were applied.

In the normal PG model the variation on the texture of the canvas is visualised and the individual brush strokes of the writings can be identified in the mesh model (Figure 309). Capturing a PG dataset when the object is placed on a light table provides us with a series of transmitted images, where the brush strokes and the writing appear emphasized. Similarly, in the resulting model both the writings and the application of colour are more discernible (Figure 310). The main features revealed in the IR image of the testers were the texture of the canvas and the legibility of the writing. The same features are detectable in the PG model in the IR spectral area (Figure 311). The tester was also captured under trans irradiation and the legibility of the writings is enhanced in the resulting model, as happens in the still images (Figure 312). A detail was also captured using a USB microscope leading to the detailed 3d reconstruction of a small area of the tester, which revealed features such as cracqueleure, and tiny losses at the level of millimetres, difficult to visualise using macroscopic means (Figure 313).

[56] See Digital Library, folder section 5.4

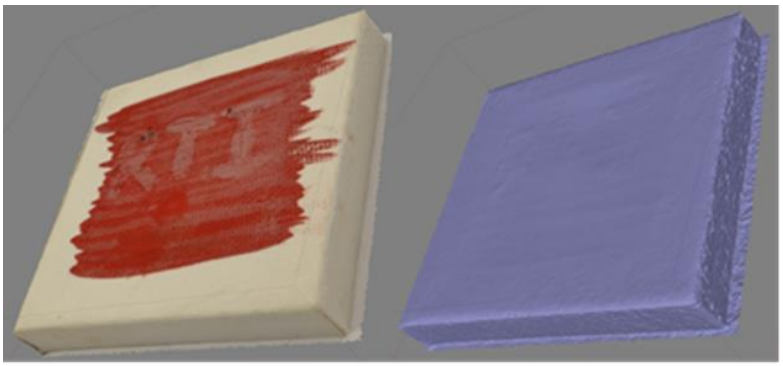


Figure 309: Tester 3, normal PG renderings (Image author's own).

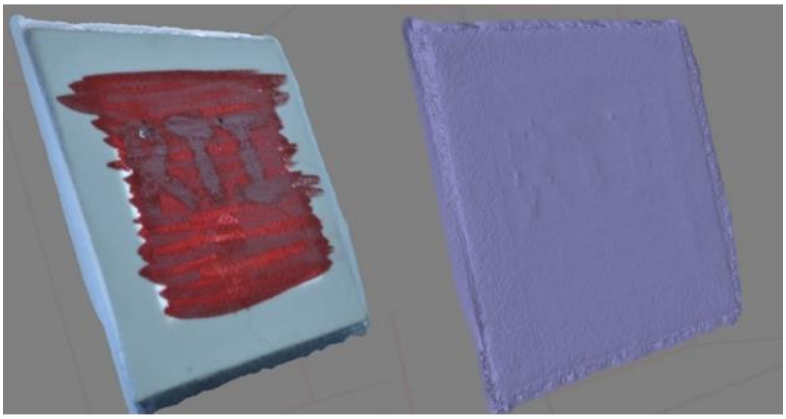


Figure 310: Tester 3, trans illumination PG renderings (Image author's own).

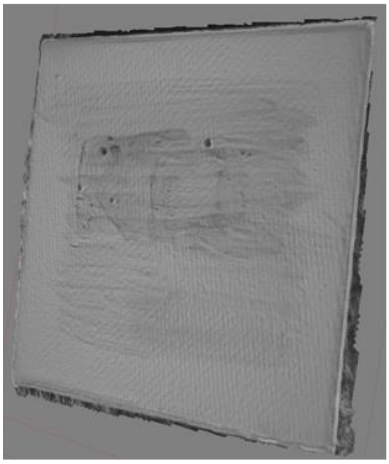


Figure 311: Tester 3, IR PG renderings (Image author's own).

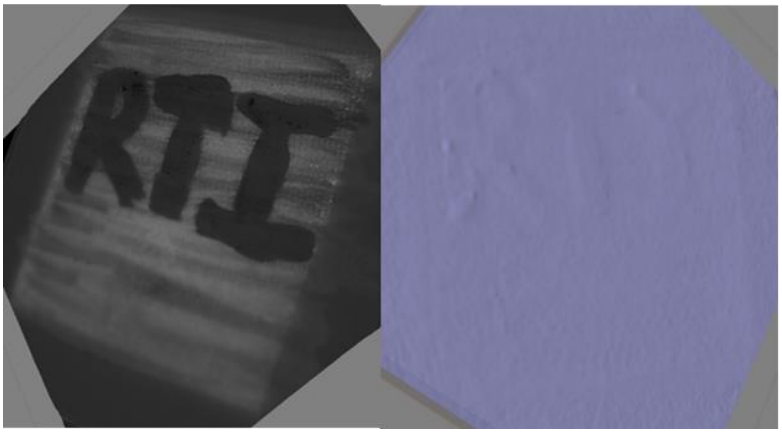


Figure 312: Tester 3, trans irradiation PG renderings (Image author's own).

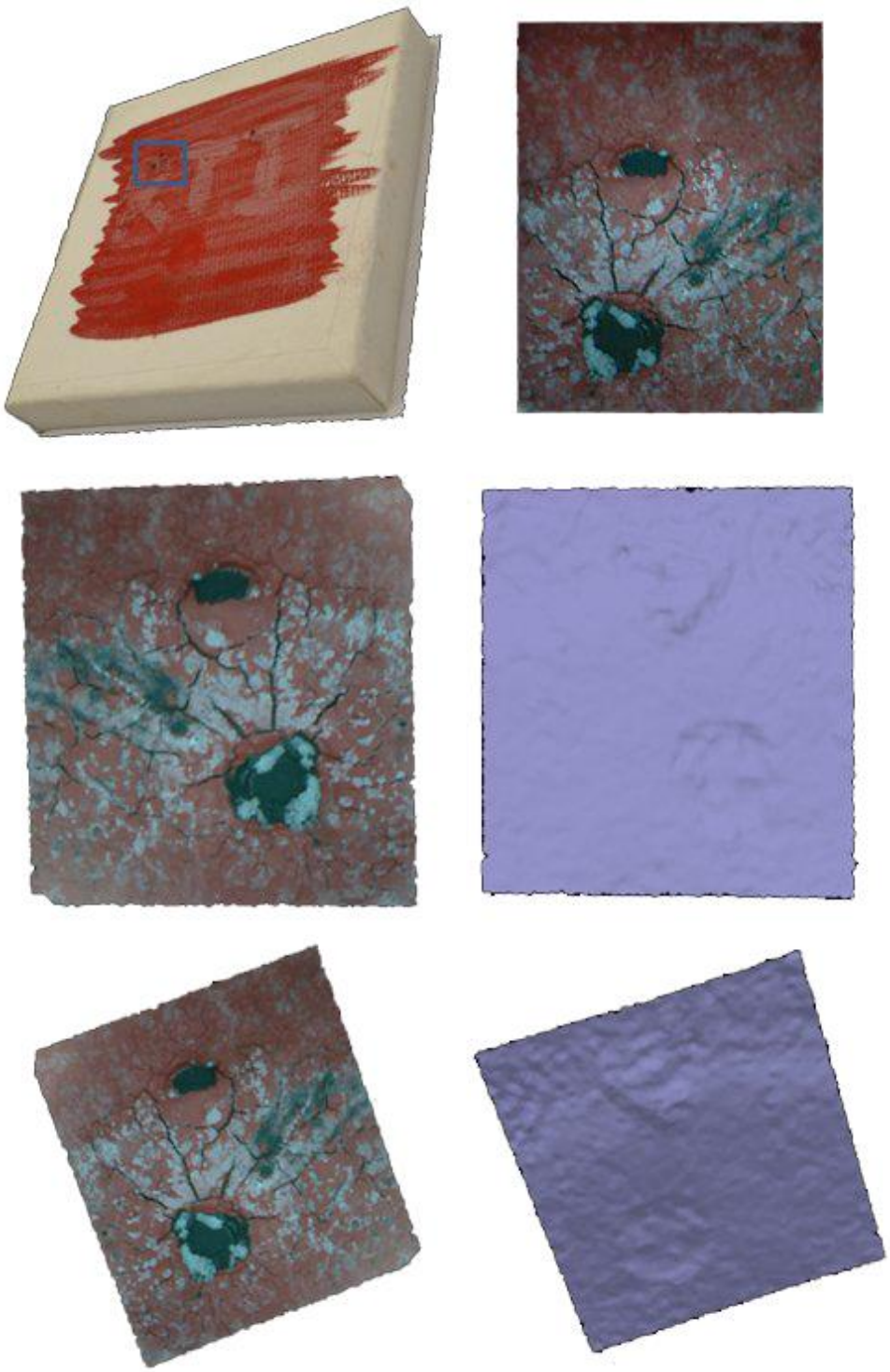


Figure 313: Detail of Tester 3. Micro-PG, renderings of mesh and textured PG model (middle and below). Normal PG model (top left) and microphotograph (top right) (Image author's own).

The four models were compared based on the readability of the writing, the visualization of the substrate and the painting layer. The writing is legible in all the models, but it appears to be emphasized in those captured under transmitted light. This is evident in the comparison of the mesh models, where the relief detail of the writing is emphasized in the trans-illuminated model. Not only the surface topography, but also the comparison of the textured models leads to this conclusion. In particular, the trans irradiation models provide the best results because of the contrast between the carbon black pigment used for the writings, which appear opaque in the infrared, and the red pigment which appears transparent (Figure 314).

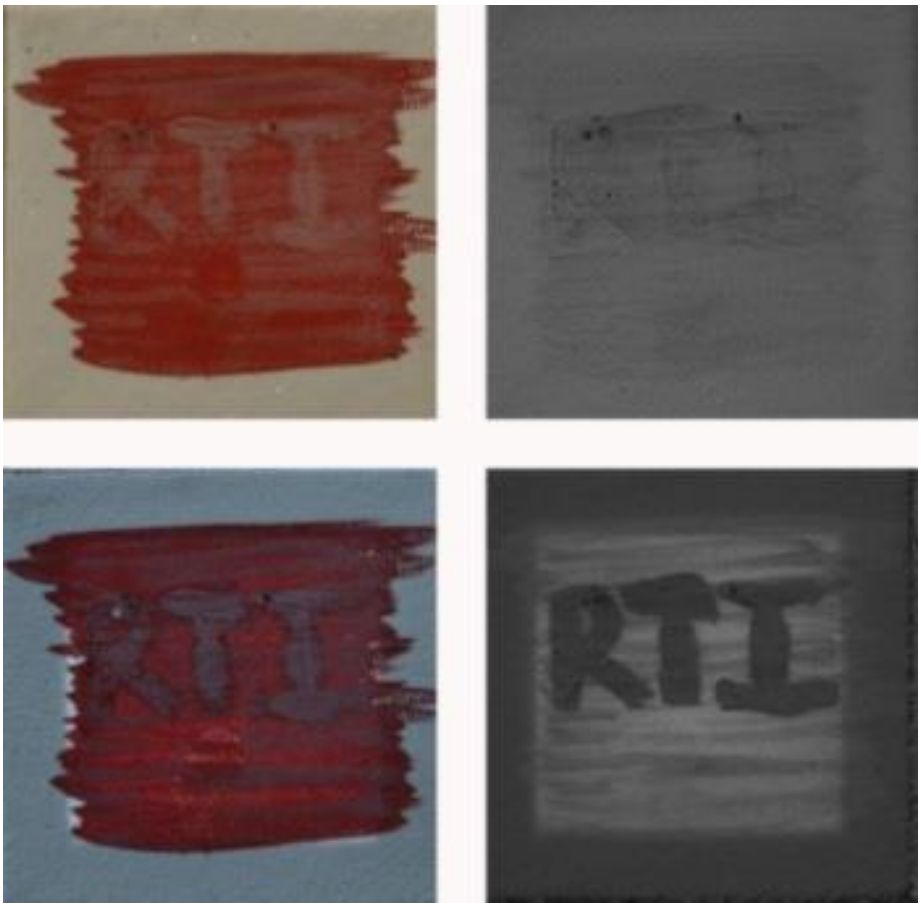


Figure 314: Tester 3, comparison of writing legibility, clockwise from top left, normal model, IR-model, trans irradiation and trans illumination model. Colour renderings (Image author's own).

The substrate was visualised more effectively in the reflected IR model. The canvas texture is emphasized as the infrared radiation penetrates the colour layer. An indication is also given by the other models (Figure 315).
The painting strokes appear clearly in the normal model, but the trans illumination enables a more complete study. The application of colour can be examined through the differences of the width of the painting layer. Moreover, the trans illumination reveals the cracking of the paint layer. The IR model does not provide any detail about the painting stokes, as they appear only as shadows (Figures 316-317).

Still imaging can provide evidence for the study of the features already described, but their visualization in 3d space offers opportunities for enhanced study and advanced documentation by providing an improved representation of the three dimensionality of the painting surface. Results are summarised in Table 15.

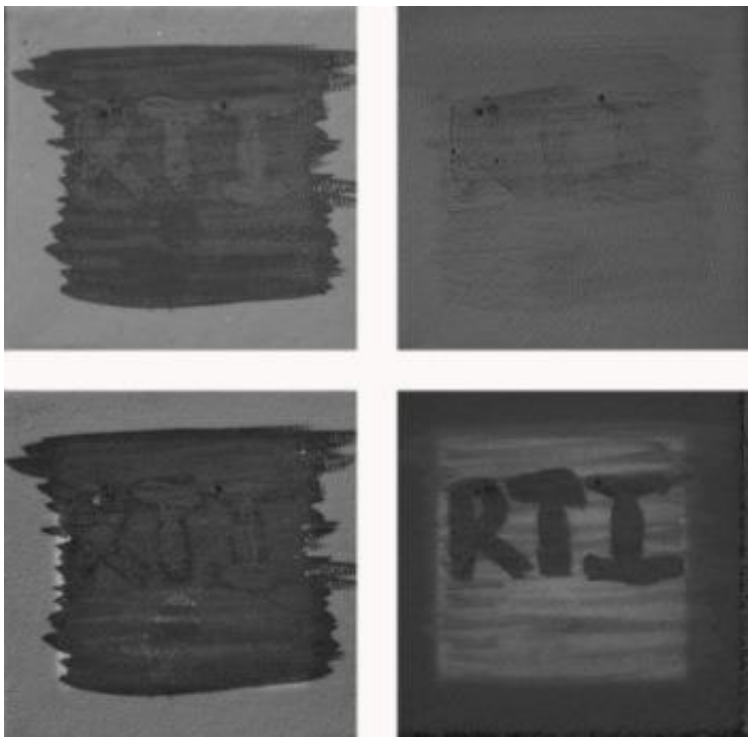


Figure 315: Tester 3, comparison of writing legibility, clockwise from top left, normal model, IR-model, trans irradiation and trans illumination model. Greyscale renderings (Image author's own).

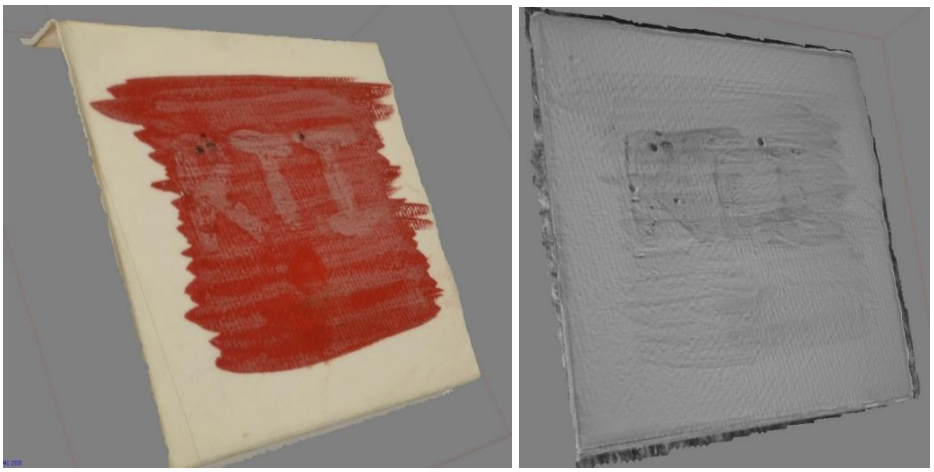


Figure 316: Tester 3, comparison of the substrate visualization in normal (left) and IR (right) PG models (Image author's own).

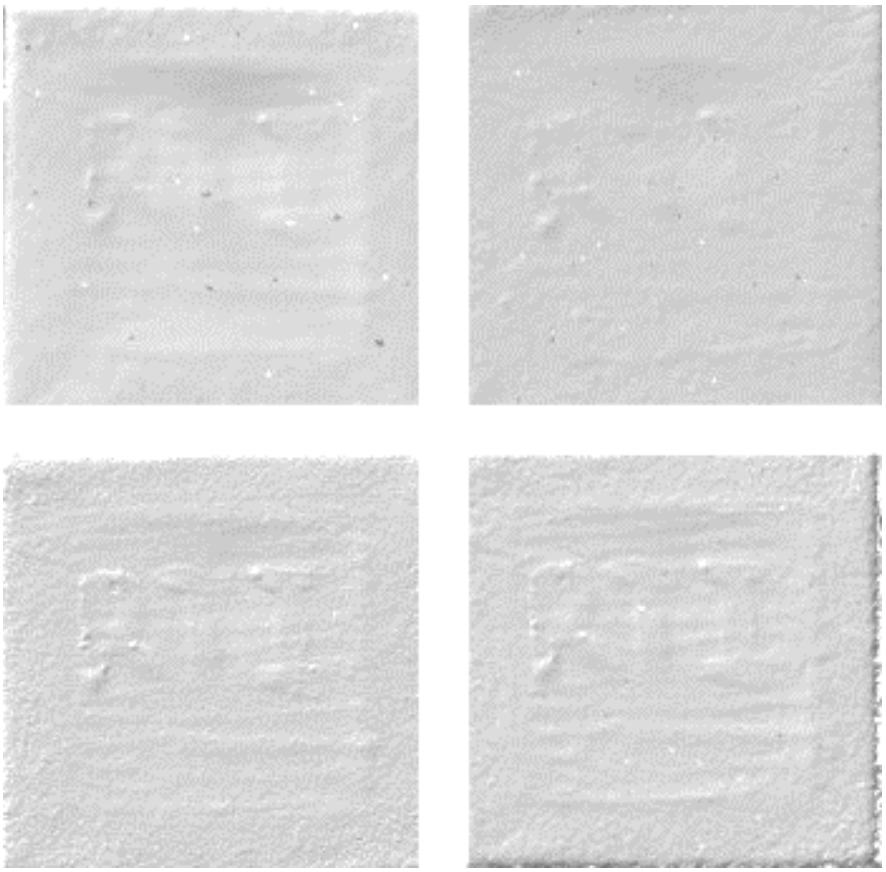


Figure 317: Tester 3, comparison of writing legibility, clockwise from top left, normal model, IR-model, trans irradiation and trans illumination model. Greyscale renderings (Image author's own).

Table 15: Summary results for the PG capture of tester 3. Deeper tones of colour represent higher efficiency.

	DETECTION OF THE OVERPAINTED WRITING	MATERIALS AND TEXHNIQUES			CONDITION REPORTING	
		SUBSTRATE VISUALIZATION	STROKES DETECTION	IMPASTO	CRAQUELURE	LOSSES
NORMAL						
NORMAL MICROSCOPIC						
REFLECTED IR						
TRANS VISIBLE						
TRANS IR						

5.4.2.2 Archaeological materials

5.4.2.2.1 Ceramics

In case of the amphora fragment and the geometric kantharos it was easy to capture appropriate data for 3d model reconstruction as the optical properties of the material are ideal, meaning the textured, not shiny surface of coarse ceramic ware. Although the objects have complex shapes handling was easy due to their stable state and reasonable size. As a result method 2 was preferred for data capture. For the amphora, in order to acquire a complete dataset of images all over the object, foam was used for positioning the object at the correct position. In total 169 images were captured for the amphora and 108 for the kantharos. Before loading the photos pre-processing is recommended so as to delete unwanted background in Photoshop. Processing uncompressed images is preferred but the necessary processing time and computational power needed is significantly higher. In order to overcome this problem the images were processed in JPG format. The photos were aligned successfully (Figures 318-319).

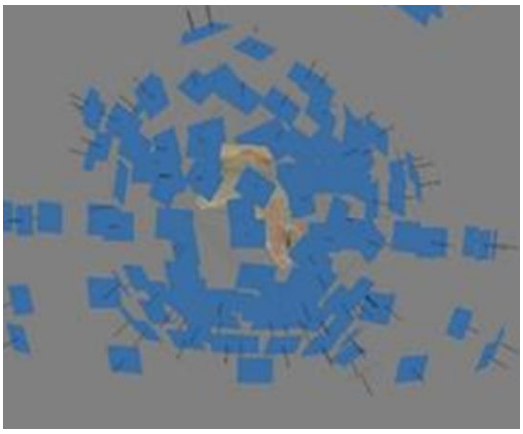


Figure 318: Amphora processing phase, cameras orientation, Agisoft Photoscan screenshots (Image author's own).

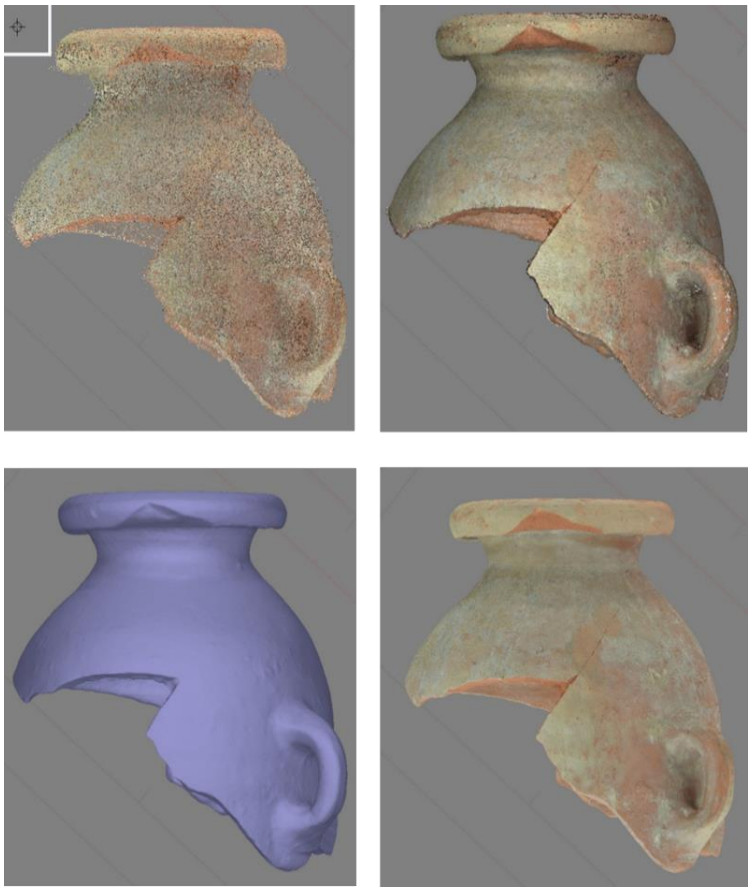


Figure 319: Amphora processing phases, sparse and dense point cloud (top) mesh and textured model (below). Agisoft Photoscan screenshots (Image author's own).

Contrary to the kantharos and the amphora, the skyphos surface is shiny because of the presence of black glaze, so it was captured with a soft box. Instead of pre-processing there is the option to apply masks in the photogrammetry software so as to avoid confusion of images and incorrect reconstructions. Finally, after masking, 102 images were aligned successfully (Figures 320-321).

Figure 320: Skyphos processing, masking of image in Agisoft Photoscan, camera orientation, Agisoft Photoscan screenshots (Image author's own).

Figure 321: Skyphos processing, mesh and dense point cloud. Agisoft Photoscan screenshots (Image author's own).

3d models of the vessels reveal losses, not only in case of missing parts but also abrasion and flaking. Other processes responsible for losses, such as spalling (a surface degradation in which tiny particles detach and fall off) or pigmentation cannot be detected. However, this type of degradation will be recognizable by the differentiation in texture. Alterations and surface damage such as pits, chips, craquellere, scratches and cracks are easily detectable. The presence of stains causing discoloration of surfaces can be noticed, but it should not be compared by the differentiations in colour introduced by poor lighting during data capture. The presence of foreign material on surfaces in the form of accretions, depositions, and efflorescence is distinguishable. Also, the remains of conservation materials may be noticeable. Manufacture evidence can be revealed, such as maker's marks, usually fingerprints in the area of the handles, inclusions and burnish marks, imperfections in the gloss occurred due to uneven, either too low or too high temperature in the kiln (Figures 322-324).

Figure 322: Amphora fragment, renderings of textured and mesh PG 3d models (Image author's own).

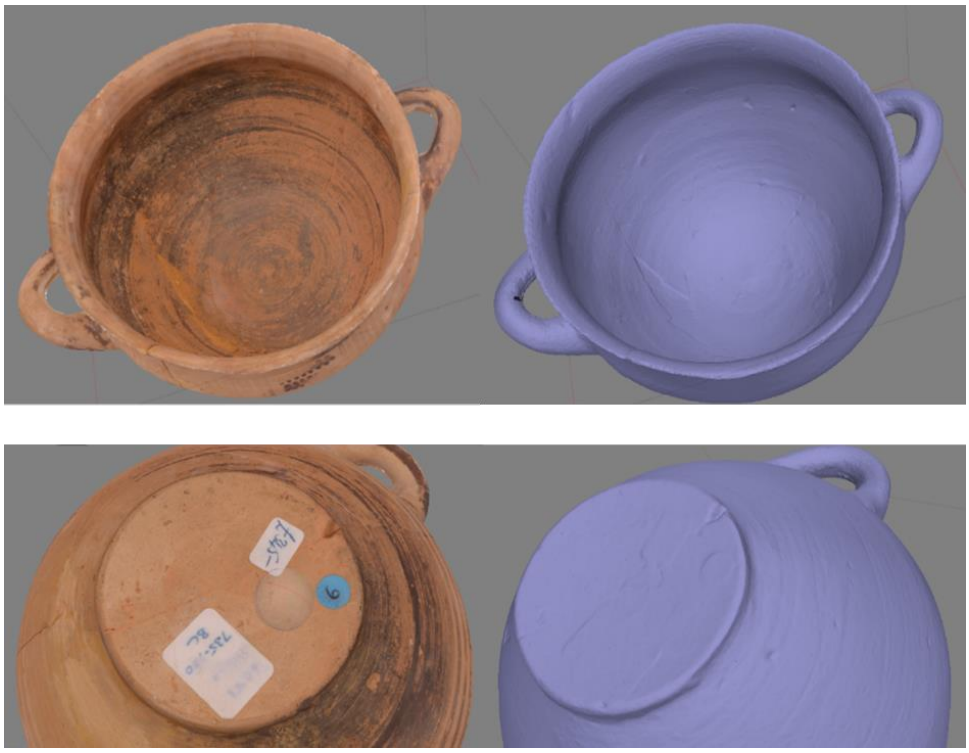


Figure 323: Geometric kantharos, renderings of textured and mesh PG 3d models (Image author's own).

Figure 324: Detail of gnathian skyphos, renderings of textured and mesh PG 3d models (Image author's own).

Analysis of the results from virtual examination of 4 ceramic vessels reveals that the features that occurred mostly and were observed in the PG models were the old labelling, manufacture evidence and decoration details. Moreover characteristic alterations and/or damages were recorded such as chipped, discoloured-stained surfaces with deposits-encrustations at a flaking state, as well as abrasions, inclusions, losses, split/fractured and cracked objects. To a lesser extend accretions, fingerprints, scratches and disjoined fragments were observed.

The disadvantages of 3d models regarding conservation examination of ceramics are relevant to material aspects other than the optical properties. Characteristic examples are the weight, temperature and humidity of the object, which indicate the condition of the artefact and can't be accessed virtually. In addition, the instability is among the features that cannot be accessed virtually. Physical contact is necessary so as to lead to sound conclusions regarding weak joins and similar features. In case of objects captured using a soft-box approach the reflectivity of the surface is not visualised accurately. The PG models of both gnathian vessels appear unrealistically dull and it is difficult to define the severity of loss of lustre, which is an alteration-damage feature that should be recorded and taken under consideration in visual analysis.

In the geometric kantharos areas which were originally painted, even if the colour is totally lost, appear slightly differentiated in texture and colour in the visible spectral area. However, this differentiation is more vivid in the infrared, as well as the faded painted designs, which appear to be emphasized. The infrared model of the pot enables an enhanced method for examination, not only because of the advanced legibility of the designs, but also because of the ability to study them in a 3d space (Figures 325-326).

Figure 325: Detail of geometric kantharos, visible (top) desaturated (middle) and IR image (below) (Image author's own).

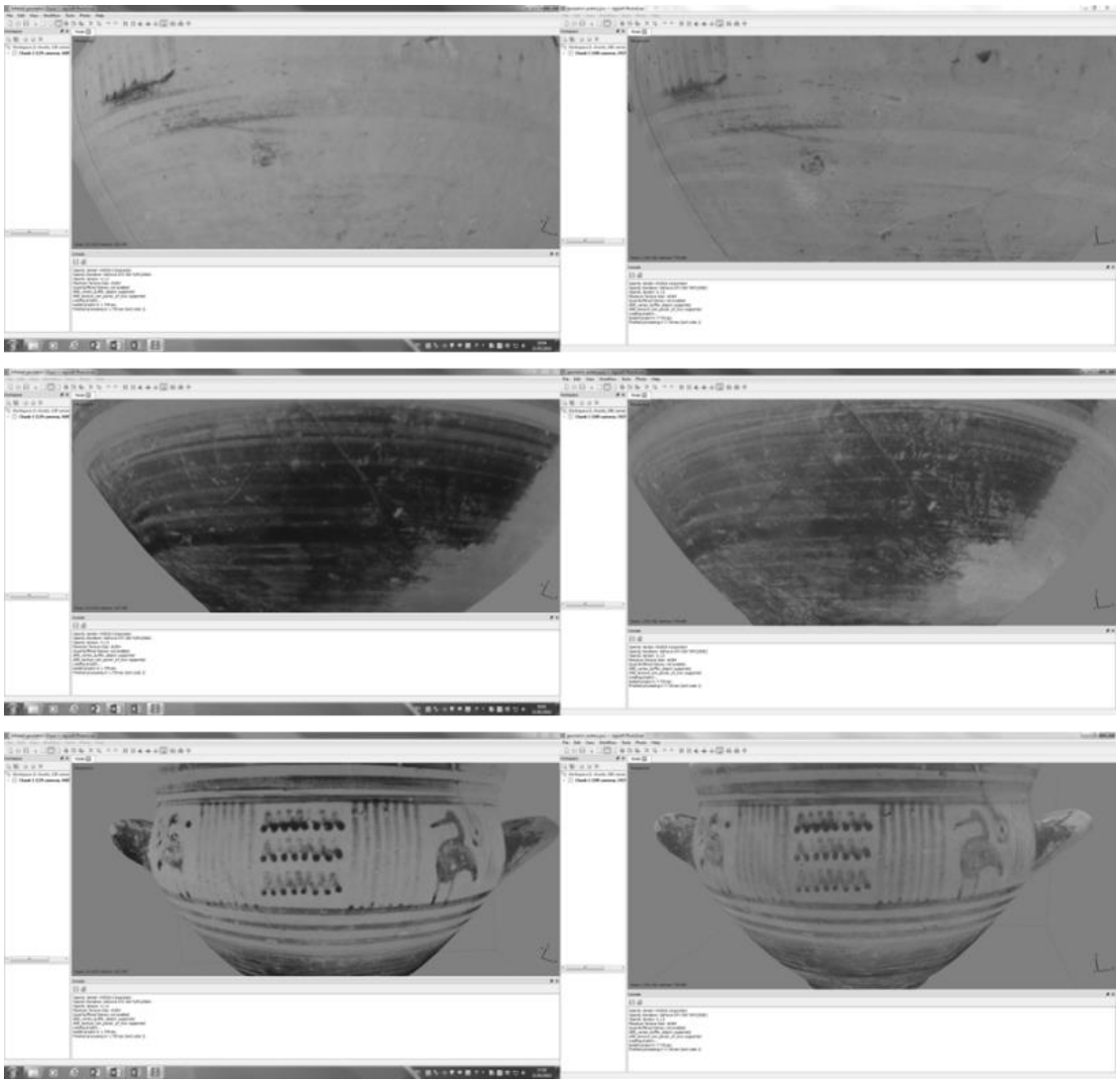


Figure 326: Comparison of renderings of 3d model of geometric kantharos in the IR (left) and visible (right) spectral region (Image author's own).

5.4.2.2.2 Glass

Interaction between light and glass causes a combination of optical phenomena; refraction, transmission and reflection of light. As a result it is impossible to calculate the camera alignment and reconstruct the model. The solution proposed for data capture of other reflected surfaces with the soft box proved to be insufficient in the case of glass. The resulting models are unacceptable.

5.4.2.2.3 Metal

The iron sundial fragment is very fragile and it is highly likely to further deteriorate if it is turned upside down. Moreover, the other part of the sundial is the chalk material, applied for secure lifting, which is of low importance for the study of the object. For these reasons, only one side was captured using method 1 (Figure 327).

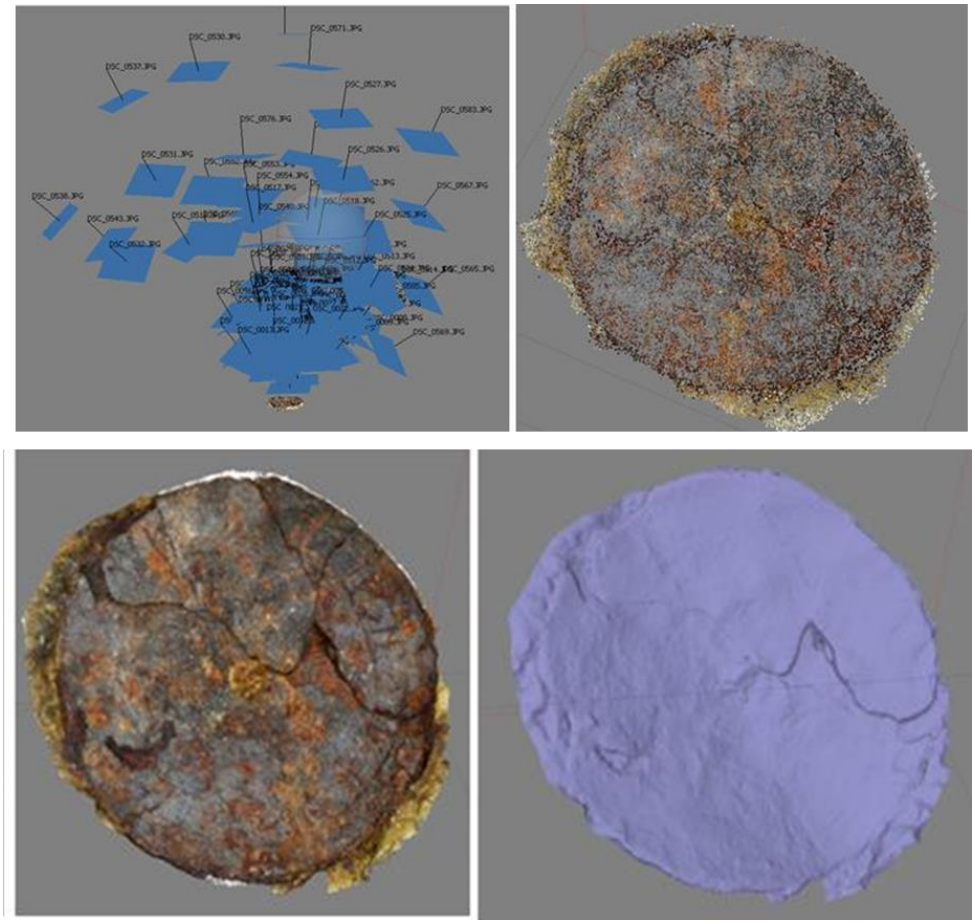


Figure 327: Sundial processing phases (clockwise from top left) camera orientation, point cloud, mesh and textured model (Image author's own).

For the coin microscopic data capture was tested and gave results of low quality. Problems encountered during the data capture were the uncontrollable lighting conditions, as the microscope lights couldn't be turned off in this specific USB microscope model, and because the movement of the microscope caused blurring in a number of images (Figures 328-329).

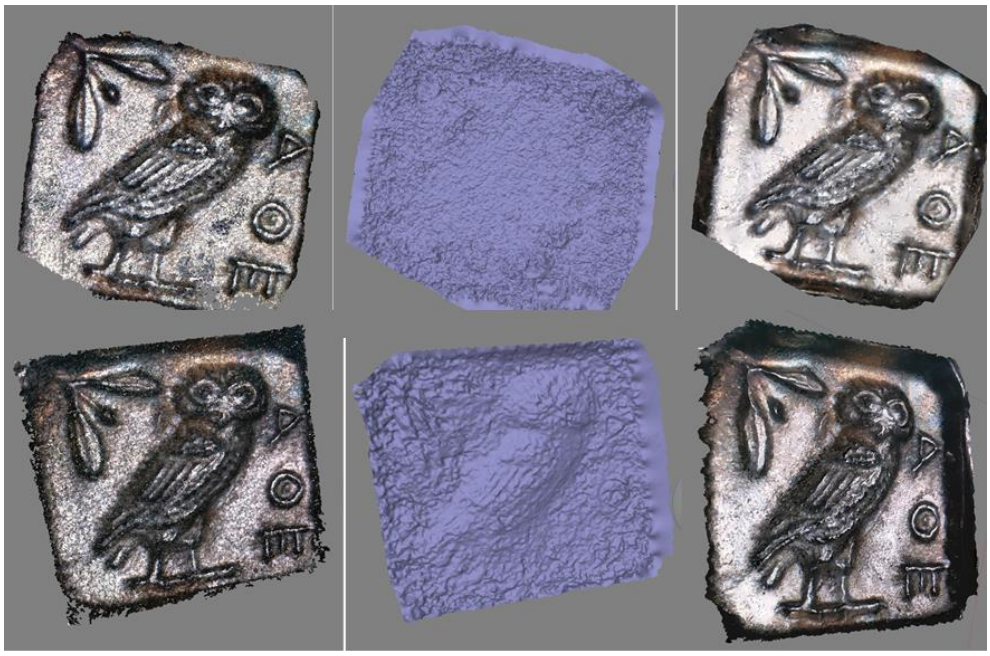


Figure 328: Microscopic PG phases (from left to right) point cloud, mesh and textured model (Image author's own).

Figure 329: Microphotographs, silver coin, detail, captured with microscope lights on (left) and off (right) (Image author's own).

Via virtual examination of metals many forms of corrosion damage can be identified. In general 3d models can successfully visualise general corrosion, as identified by the presence of uniform rust as well as other forms of patination such a tarnishing, dulling, staining or discoloration. Localised corrosion, usually appearing in the form of pitting which penetrates into the metal, is identifiable as well. Similarly, crevices can be observed, in particular when they are associated with solids deposited on a surface, a phenomenon usually referred to as deposit attack. Environment assisted cracking corrosion

phenomena in the form of stress corrosion cracking are observable. In case of the sundial the 3d model successfully visualises both physical and chemical damage. The features observed were the following (Figure 330):

- Cracks and distortions,
- discoloured- stained surface,
- deposits-encrustations and accretions,
- faking/delamination,
- decoration-incisions (partly visible),
- missing parts-losses and
- local corrosion.

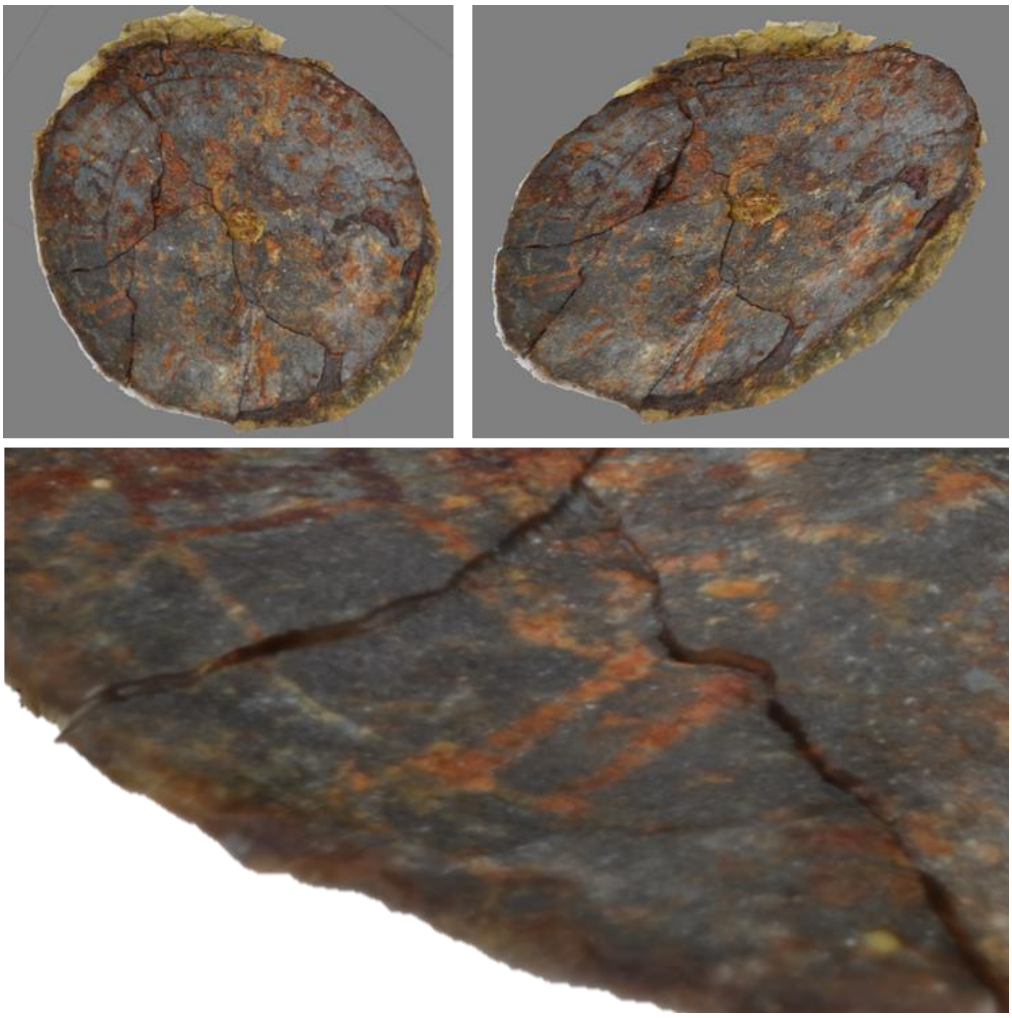


Figure 330: Renderings from PG model of sundial fragment (Image author's own).

5.4.2.2.4 Stone

Data capture was performed according to method 2. The lighting conditions were uncontrollable, including open windows and a number of artificial lighting sources in the room (Figure 331). For drum 3 a large number of images (144) were captured, and a further 108 for drum 2. An initial attempt to align the images without pre-processing or masking resulted in incomplete reconstruction. The main issue was the misalignment of the images from the base (Figure 332). A second attempt to align the images after masking proved to be successful. Areas with reflection were masked so as to avoid unrealistic reconstruction. The results were acceptable (Figure 333).

Figure 331: image captured under uncontrollable lighting in the British Museum (Image author's own).

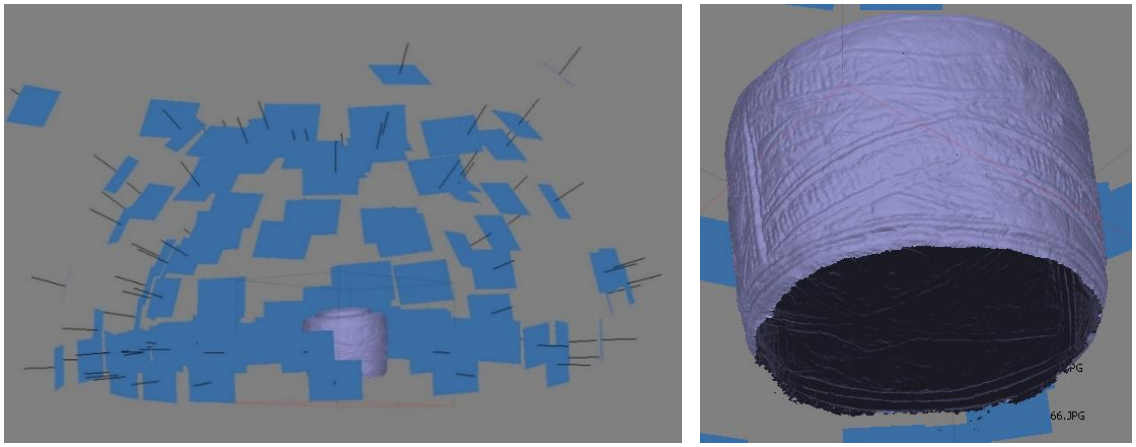


Figure 332: Misalignment of the images from the base (Image author's own).

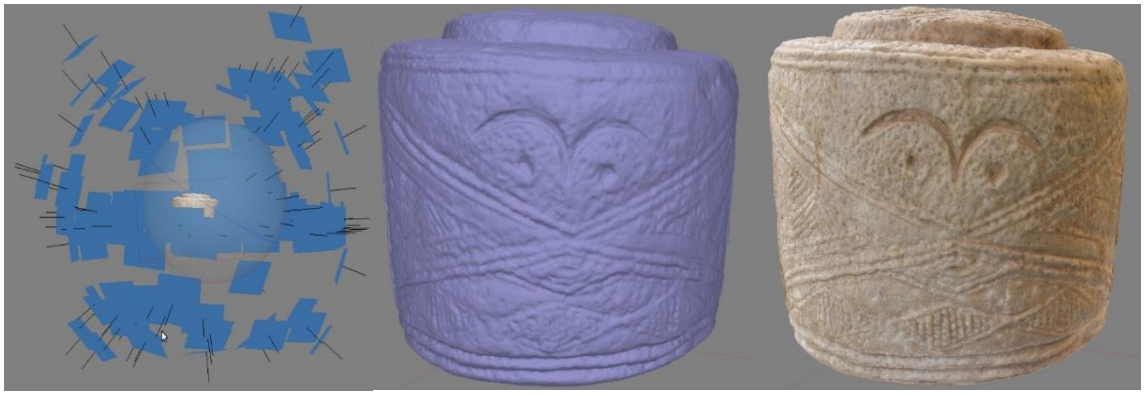


Figure 333: Drum 3 processing phases (Image author's own).

Via virtual examination loss of stone material can be detected. Selective weathering is observable because of the morphological changes introduced. For example the distinctive patterns of alveolar weathering and pitting can be easily differentiated. Also, anthropogenic impact weathering, such as scratches, can be located. Discoloration, soiling and encrustation are among the phenomena that can be identified. In the Folkton drums models of the following phenomena were observable (Figure 334):

- old labelling,
- manufacture evidence,
- decoration,
- scratches,
- discoloured-stained surface,
- chipped areas-losses
- pitting and
- material interface damage.

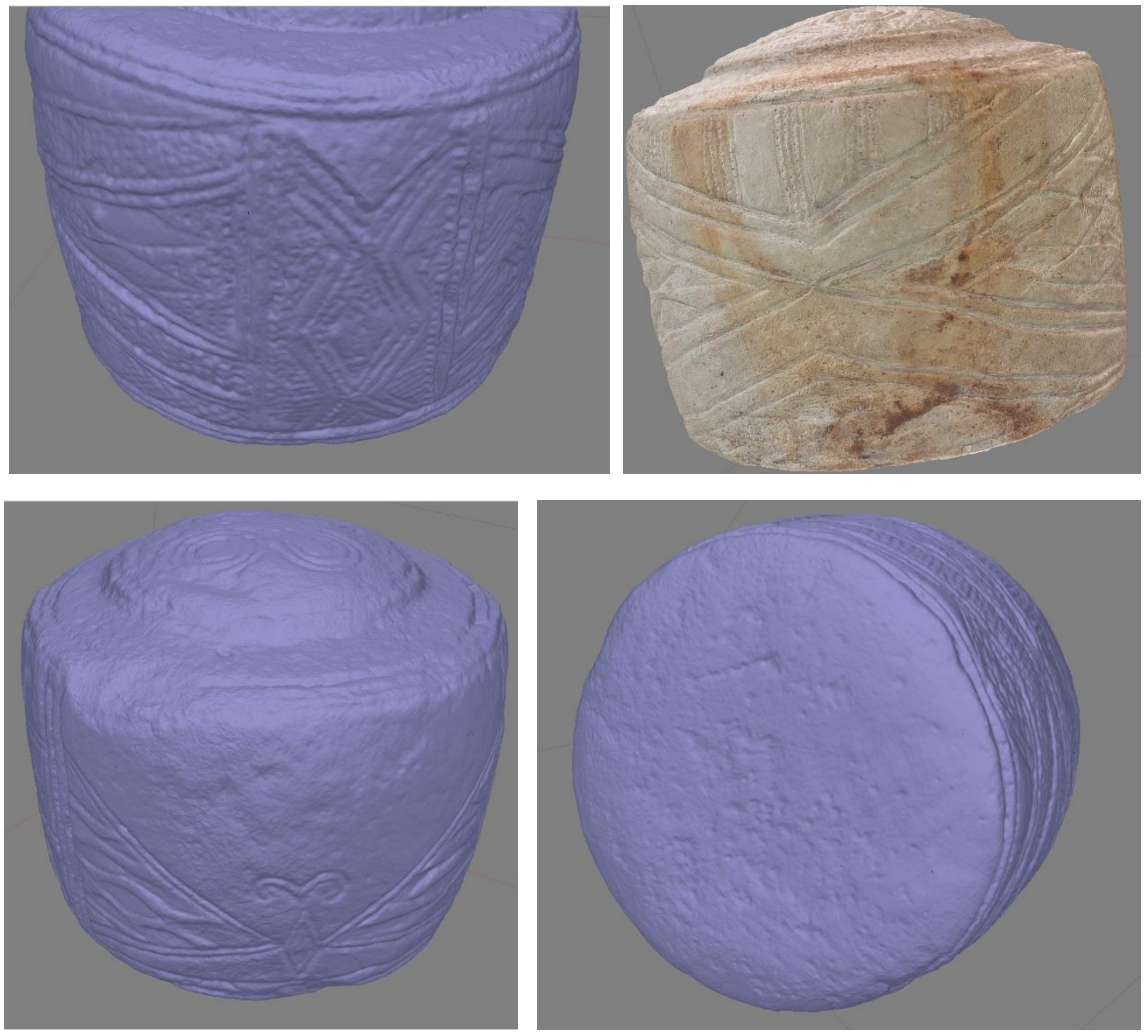


Figure 334: Renderings from PG models of Folkton Drums No 2 and 3 (Image author's own).

5.4.2.2.5 Textile

The textile was captured with method 1 because it is too fragile to withstand any manipulation and handling. Data capture was performed both with and without back light. The microscopic PG models of the textile, similar to the coins one, cannot be used for virtual conservation assessment, as the texture is poorly visualised resulting in unrealistic reconstructions, mainly due to the combination of reflectivity and uncontrollable lighting conditions during capture.

5.4.2.3 Digital image processing

Another advantage is the opportunity to create illustrations, profiles and sections much easier than following the conventional approaches. Different forms of visualization for sections of vessels can be produced in 3ds max and other similar 3d software (Figure 335) while further processing of these renderings can result in illustrations similar to the traditional ones (Figure 336). Also, the opportunity to perform dimensional study of the artefact is an enhanced option compare to 2d approaches, even in areas which are difficult or impossible to measure (Figure 337). The ease of use and the productions of detailed illustration which would be impossible using other methods can be demonstrated in the case study of the sundial. The deformation of the object is visible in the profile and section illustration, which are produced simply by the application of a slicing tool (Figure 338).

Figure 335: Illustrations for section of geometric cantharos created in 3ds max based on the PG 3d model (Image author's own).

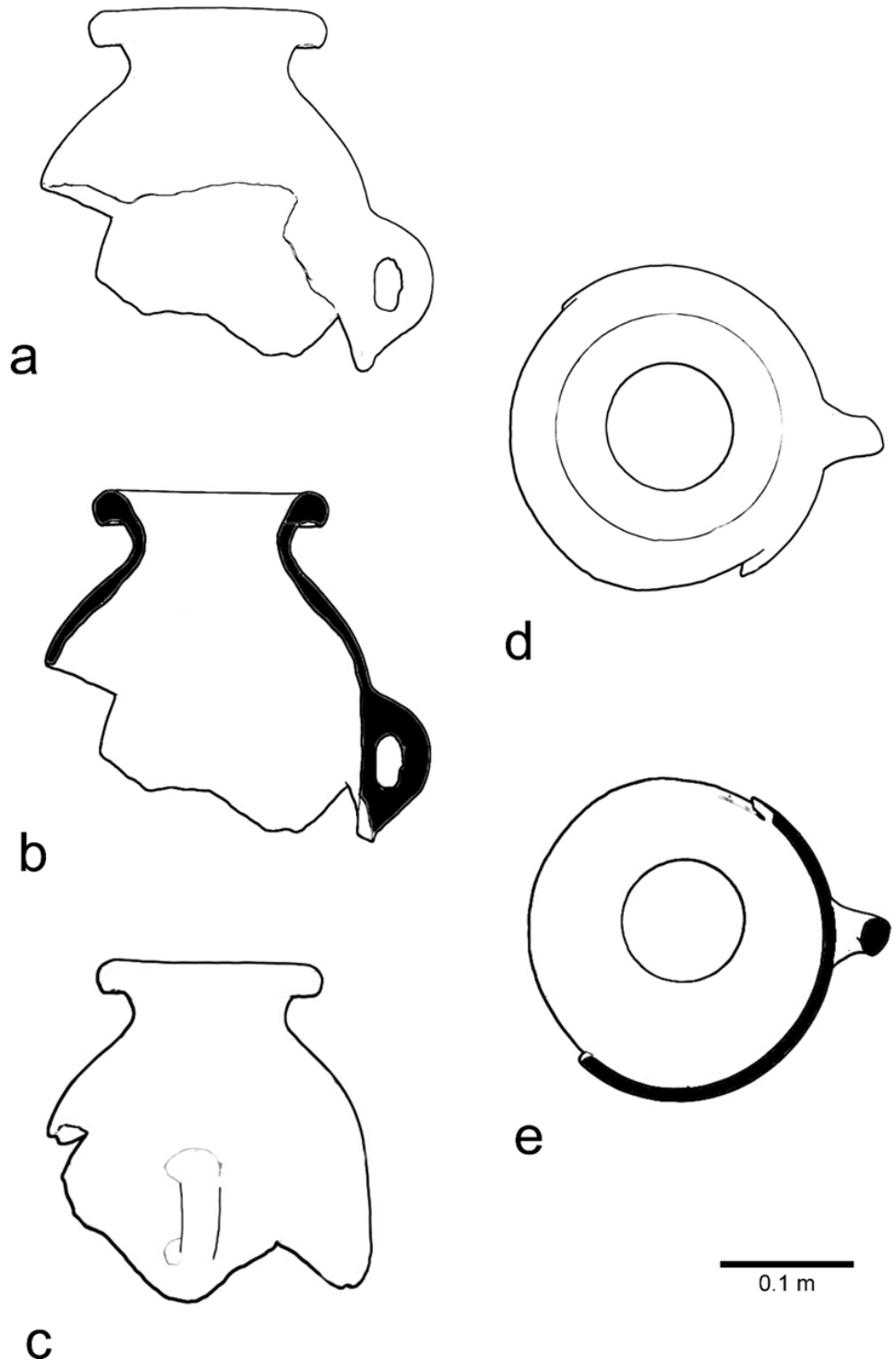


Figure 336: Illustrations created from PG 3d model, Neo-punic Amphora fragment (Image author's own).

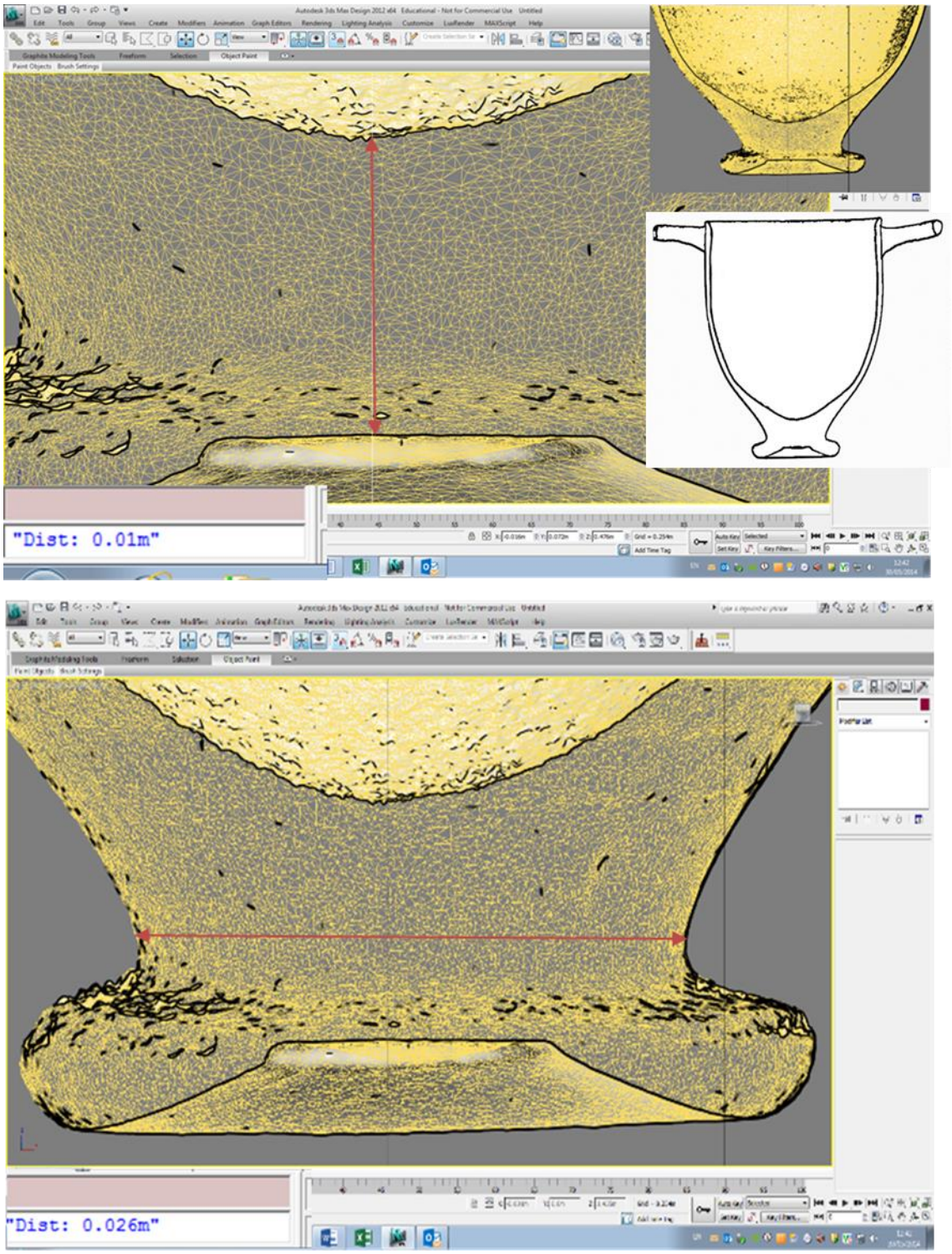


Figure 337: Dimensional analysis based on 3D model. The height (top) the diameter (below) of the foot of the skyphos is 0.01 and 0.026m respectively (Image author's own).

Figure 338: Side view and section of sundial showing the deformation of the object (Image author's own).

5.4.2.4 Virtual reconstruction

3d digitised artefacts can lead to virtual reconstruction using 3d modelling techniques (see section 2.3.2.2). Depending on the type of the reconstruction, the resulting models find various uses (see 4.4.1). For example the non-photorealistic rendering of the virtually restored skyphos shown in Figure 339, can be useful for treatment proposals and documentation, as it emphasizes the new additions.

Figure 339: Virtual reconstruction of gnathian skyphos. Non-photorealistic rendering created in 3ds Max. The new additions were rendered in red, yellow and green (Image author's own).

Beyond documentation, virtual reconstruction assists in case of difficult remedial conservation operations. In the case of the amphora the physical restoration would be time-consuming because of the size and the large area that needs to be restored. After classification of the fragment (Figure 340), via 3d modelling, the missing area can be designed so as to match the geometry of the original ceramic material (Figure 341). In case of symmetrical features replication is extremely easy in 3d software (Figure 342). By applying an appropriate material to the replicated part, the final virtual reconstruction, shown in Figure 343, represents the object as if it has been physically restored.

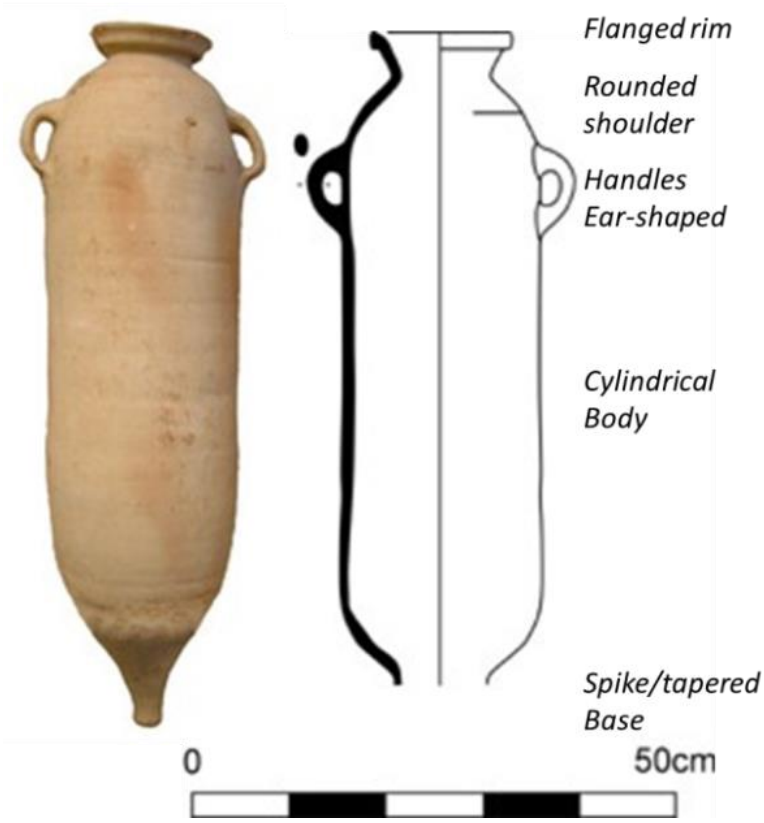


Figure 340: Van der Werff 2 Amphora type. Image retrieved from the digital resource of Roman Amphora of the University of Southampton

Figure 341: Virtual reconstruction of the amphora, detail. Non-photorealistic rendering created in 3ds Max (Image author's own).

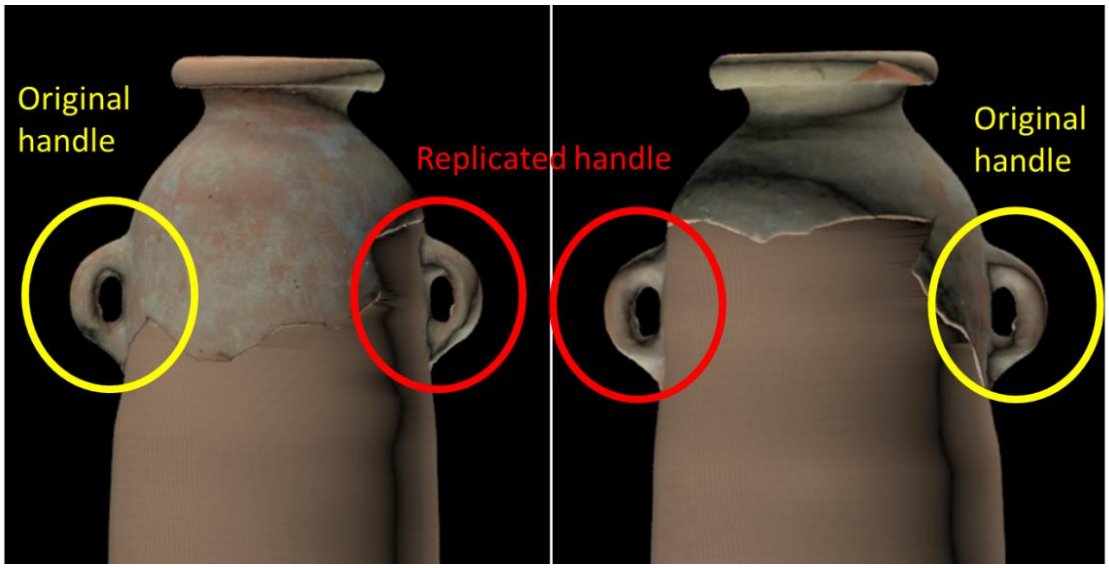


Figure 342: Virtual reconstruction of the amphora handle, detail. Rendered in 3ds Max (Image author's own).

Figure 343: Virtual reconstruction of the amphora, rendered in 3ds Max (Image author's own).

For the purposes of the present study two vessels of similar type (chous) were 3d digitised using PG. Both have plump shape, a trefoil mouth and a single handle. The one is incomplete and the other is complete (Figure 344). Via 3d modelling the handle of the complete vessel can be virtually removed, scaled and attached to the incomplete vessel (Figure 345). In order to represent the chous as if it was complete not only the geometry but also the materials need to be reconstructed. This process is similar to conventional restoration operation, but easier to execute. The material of the body was replicated and applied to the handle, resulting in the final virtual reconstruction of the chous (Figure 346). More advanced application of 3d modelling and virtual reconstruction are discussed in Chapter 6.

Figure 344: Chous with a missing handle (left) complete chous (right). Renderings created in 3ds Max (Image author's own).

Figure 345: Attachment of handle from complete chous (Image author's own).

Figure 346: Virtually restored chous. Renderings created in 3ds Max (Image author's own).

5.5 Evaluation

Simple visual comparison gives a general idea about the application of RTI and PG. The use of a formalised evaluation methodology assists the analysis of results, and can potentially help in defining the effectiveness and the limitation of the techniques, and lead to safe conclusions based on the collected data regarding their application in conservation. In order to set up an evaluation framework the criteria-parameters and the sample that will be used needs to be determined.

5.5.1 The evaluation framework

The objects visualised for the purposes of the present study were used as a sample for the evaluation. The deterioration of different material types is related to physical damage and chemical deterioration, and can take various forms under the influence of air pollution, salts, and bio-deterioration. The colour, texture and morphology of surfaces can be associated to known degradation phenomena and corrosion types. A long list of features is observable offering valuable information for an objects' characterization. The most common phenomena observed on materials are categorised based on the differentiation in colour and other optical properties, the geometry and the texture morphology (Table 16).

For the numismatics case study the set of parameters was carefully selected so as to cover this specific field of study. In addition to the parameters relevant to corrosion and damage of metals, a set of criteria were applied for identification, manufacture and use evidence. The readability of the legend and the enhancement of the design were the identification criteria used. The manufacture parameters seek to identify relevant evidence, such as the striking angle. Further analysis of the observed features can reveal information about the previous treatments as well as use evidence (Table 17).

For the painted surfaces the selected parameters for the evaluation are based on stratigraphy; the varnish, paint layer and substrate, and they include features related to physical damaged already mentioned in the general evaluation parameters.

Table 16: Common features observed on objects related to degradation effects and categorization according to alterations in colour, optical properties, geometry and/or texture

Features	**Alterations**
Corrosion, Soiled surface, Formation of corrosion products, Salts efflorescence	Colour, Other optical properties, Geometry, Texture
Delamination, Disjoined, Glue failure, Pustules of corrosion, warty corrosion	Geometry, Texture
Abrasion-scratches, Accretions-depositions-crusts, Bronze disease or localised chloride corrosion, Manufacture evidence, Mould	Colour, Other optical properties Texture
Decoration /stratigraphy, Material interface damage	Colour, Texture
Adhesive residue, Dirty/dusty/ Superficial dirt/dulling/loss of lustre, Iridescence, Tarnishing	Colour, Other optical properties
Discoloured-Stained-Faded-Yellowed	Colour
Friable – Powdery, Loss, Restoration materials' remains, Rough surface, weeping surface	Other optical properties, texture
Break/ Split / Fracture, Brittle/ embrittled, Cracks, Distorted, Severe loss-fragmentation, Spalling - break up and detachment of fragments into wedges and flakes	Geometry
Fingerprints, Flaking, Grazed, Holes/pitting, Stripping - early treatments, Blistered surfaces, Crumbly disintegration	Texture

Table 17: Features selected for the evaluation of numismatics virtual visual analysis

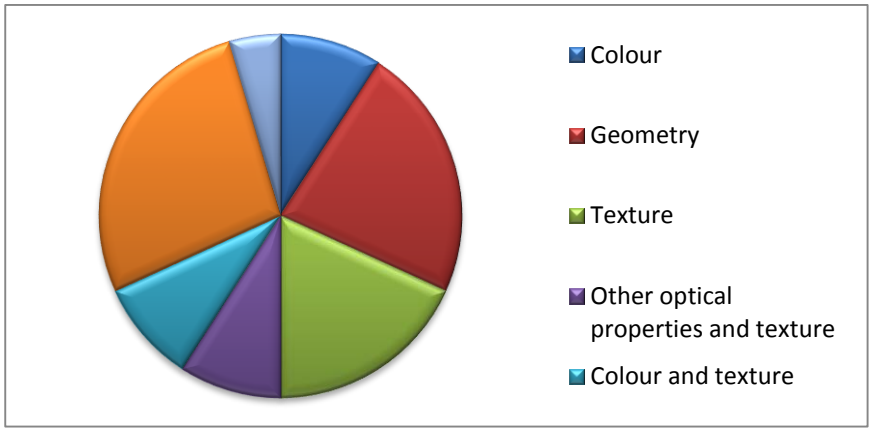
FEATURES		KEY
IDENTIFICATION	LG DS	*LG=LEGEND* *DS=DESIGN* *AM=ADDITION OF NEW MATERIAL* *ENC=ENCRUSTATION* *DP=DEPOSITIONS* *AC=ACCRETIONS* *UC=UNIFORM CORROSION* *LC=LOCAL CORROSION* *AC= ACTIVE CORROSION* *ML=MATERIAL LOSS* *FL=FLAKING* *PT=PITTING* *CR=CRACKS* *SC=SCRATCHES* *WA=WARTS* *MD=MINOR DEFORMATIONS* *ST=STRIKING EVIDEVCE* *MAD=MAJOR DEFORMATIONS* *WA=WARTS*
ADDITION OF MATERIAL	ENC DP	
CORROSION	AC UC LC AC WA	
MATERIAL LOSS	FL PT ML	
DEFORMATION	MD MAD CR SC	
STRIKING	ST	

Although the sample collected is large, especially for RTI evaluation, and the criteria are carefully selected, it is impossible to cover all the possible cases, due to the uniqueness of finds. No one artefact is exactly like another one. Moreover, the process of evaluation of virtual visual analysis is to a certain extent subjective, depending on the evaluator, and similar to conventional visual analysis. It should be noted that sometimes artefacts may look perfectly sound to the naked eye, while below the surface the material has lost its cohesion. Also, the inherent instability and odour of objects cannot be assessed virtually via digital representations. These features may exist but are not detectable using virtual visual analysis.

5.5.2 Evaluation results

Discolouration and stains as well as labelling are easily observable via PG. Loss of lustre is not as easily detectable, in cases when the dataset was captured using the soft box approach, such as the black glazed pottery. Decoration and manufacture evidence, such as fingerprints, can be examined virtually. Damage and other features that take the form of geometric transformation is visualised effectively, such as splits-fractures, missing parts, losses, holes, distortions and disjoins. Chipped and cracked objects are also well represented in PG models, as well as abrasions and inclusions. Similarly, deposits, encrustations and corrosion, especially in the form of localised corrosion, can be examined virtually. In addition, adhesive residues and material interface damage are among the features that can be visualised perfectly in 3d models. Scratches, flaking and delamination can be detected, depending on the extent of damage.

This evaluation is based on PG 3d models reconstructed from complete datasets using high quality processing. The results are summarised in Table 18. Further analysis indicates that higher occurrence of degradation effects in PG models is associated with detection of (1) colour differentiation, (2) geometry, (3) texture, (4) other optical properties and texture, (5) colour and texture, (6) colour other optical properties and texture and (7) a combination of all the parameters. The geometrical transformation and the features evidenced by alterations in colour-optical properties and texture are dominant, followed by those depending on texture differentiations (Graph 36).



Graph 36: Occurrence of degradation effects in PG models virtual visual analysis (Graph author's own).

Table 18: Evaluation data for PG and comparison between 2D images and 3D models. KEY: 0=not existing, 1=existing and visible, 2=possible existing but not visible.

FEATURES	Ceramics				Metal	Stone			
	KANTHAROS	AMPHORA	CHOUS GNATHIA	SKYPHOS GNATHIA	SUNDIAL	DRUM3	DRUM2	2D IMAGE	3D MODEL
Discoloured-stained	1	1	1	1	1	1	1	√	√
Labelling	1	1	1	1	0	1	1	√	√
Decoration	1	0	1	1	1	1	1		√
Manufacture evidence	1	1	0	1	0	1	1		√
Chipped	1	1	1	1	0	0	1		√
Cracked	1	1	1	1	1	0	0		√
Deposits-encrustations	1	1	1	1	1	0	0		√
Losses	1	0	1	1	1	0	1	√	√
Scratched	1	1	0	0	0	1	1		√
Flaking/ Delaminating	1	1	1	0	1	0	0		√
Split/fractured	1	1	0	1	1	0	0	√	√
Abrasions	1	1	1	0	0	0	0		√
Inclusions	1	1	1	0	0	0	0		√
Accretions	0	0	1	1	1	0	0		√
Loss of lustre	1	1	2	2	0	0	0	√	√
Fingerprints	1	0	0	1	0	0	0		√
Adhesive residue	0	0	0	1	0	0	0		√
Disjoined	1	0	0	0	0	0	0		√
Holes	0	0	0	1	0	0	0	√	√
Material interface damage	0	0	0	0	0	0	1		√
Corroded	0	0	0	0	1	0	0	√	√
Distorted	0	0	0	0	1	0	0		√
Weak joins	2	0	0	2	2	2	2	-	-
Inherent instability	2	2	2	2	0	0	0	-	-

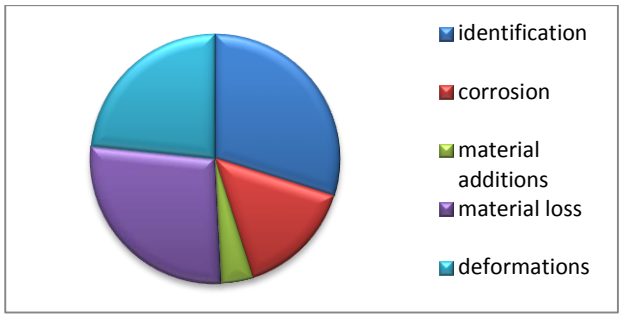
Two dimensional digital images and PG models provide identical results in features related to colour differentiation, such as discolouration/staining. This is reasonable considering that the colour information for the texture generation in 3d models derived from digital images. The visualization of other optical properties of objects in 3d models, such as glossiness, depends on the data capture followed. The reflectivity of surfaces is represented in two dimensional images more realistically than in 3d models when data capture is performed with a soft box. Alterations in shape and form, such as fractures, losses and holes can be distinguishable in two dimensional images although the ability to study them in 3d space provides enhanced perception of the condition of the artefact. Less obvious alterations of geometry and texture are visualised in a more effective way in the three dimensional model than in the static two dimensional image. Worth mentioning is that these features are of crucial importance for the conservation examination. Although drawings are common in conservation documentation a direct comparison with virtual visual analysis is impossible. Drawings represent the understanding of the viewer/illustrator and can be considered interpretative documentation. Nevertheless, it is difficult to represent features related to colour information in drawings, while geometrical information, such as form and shape can be documented using standard drawing techniques.

Through RTI visualizations features evidenced by colour, such as discolouration, staining and yellowing can be detected effectively. Similarly, features associated by texture alterations, such as blistered surfaces, crazed, crizzling, crumbly disintegration, fingerprints, flaking, grazed, holes/pitting and stripping - early treatments are represented successfully in RTI visualizations. Although RTI is not the appropriate methodology for documenting major geometrical transformations, break, splits, fractures, brittle surfaces, cracking, distortions, fragmentation and spalling can be examined virtually. More interesting is the enhanced visualization of features characterised by combinations of alterations, such as those related to both geometry and texture modifications. Characteristic examples in this category are the delamination, disjoins, glue failures, insect damage and warty corrosion. Other features are evidenced by the study of colour and texture, such as the decoration, the stratigraphy and the material interface damage. The colour and the other optical properties, revealed via RTI, are crucial for the

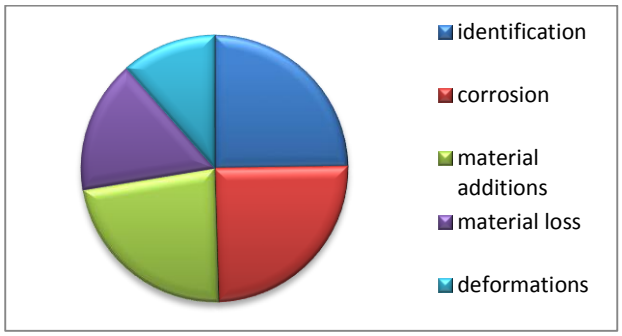
characterization of adhesive residues, iridescence, tarnishing as well as superficial dirt, dulling and loss of lustre. Also, the study of optical properties other than colour in addition to the surface morphology examination reveals the rough, friable – powdery, weeping surfaces, losses and restoration materials' remains. The combined RTI study of texture and optical properties documents abrasion-scratches, accretions, depositions, crusts, manufacture evidence, mould and bronze disease or localised chloride corrosion. By examining simultaneously all the categories the formation of corrosion products and salt efflorescence can be characterised and the soiling can be differentiated from original surfaces (Table 19).

Features related to colour (discolouration, staining, yellowing) and other optical properties (superficial dirt, loss of lustre, tarnishing, adhesive residue) are visualised effectively in both two dimensional images and RTIs. Similarly, in cases of major geometrical transformations results are quite similar. On the contrary, when the study of the texture is key for the interpretation of surface features, RTI is a better technique for documentation and recording (Table 19).

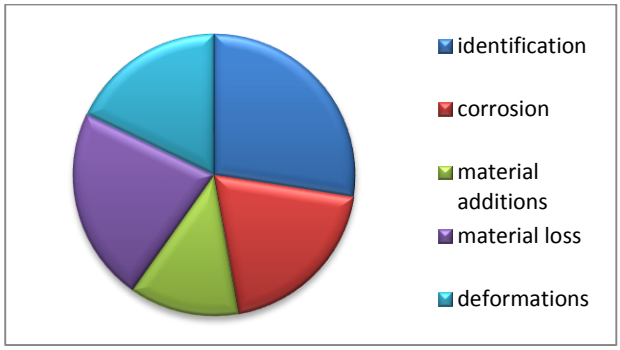
In the numismatics RTI case study the most dominant features observed were those related to coin identification, meaning the enhancement of legibility of legends and designs. Data relevant to the characterization of corrosion (active, local, uniform and warts) and loss of material (flaking-delamination and pitting) were also common. Deposits-encrustations and deformation of coins were features observed at a lesser extent. For the coins' visualizations before treatment, features for the characterization of corrosion and the addition of new material are common, followed by the material losses and deformations. After treatment the visualised coins revealed material losses and deformations to a great extent. However the corrosion characterization was observed to be significantly eliminated compared to the results before treatment. Finally the addition of material reached minimum levels (Graphs 37-39).



Graph 37: Evaluation of RTI for numismatics virtual analysis before treatment (Graph author's own).



Graph 38: Evaluation of RTI for numismatics virtual analysis after treatment (Graph author's own).



Graph 39: Evaluation of RTI for numismatics virtual analysis (Graph author's own).

Table 19: Evaluation results from RTI visualization of objects from the Derveni Tombs. Categorization of features revealed and comparison between 2D images and RTIs.

Category	Features	2D IMAGES	RTIs
Colour	Discolouration/staining /yellowing	√	√
Geometry	Break/ Split / Fracture Brittle/embrittled Cracks/ Spalling/ Torn Distorted Severe loss-fragmentation	√	√
Texture	Blistered surfaces Crazed Crizzling Crumbly disintegration Fingerprints Flaking Grazed Holes/pitting Stripping - early treatments		√
Geometry and texture	delamination Disjoined Glue failure Insect damage Pustules of corrosion - warty corrosion		√
Colour and texture	Decoration /stratigraphy Material interface damage		√
Colour and other optical properties	Adhesive residue Dirty/dusty/ Superficial dirt/dulling/loss of lustre Iridescence Tarnishing	√	√
Other optical properties and texture	Friable – Powdery/ Rough surface/ Weeping surface Loss Restoration materials' remains		√
Texture and other optical properties and colour	Abrasion-scratches Accretions-depositions-crusts Bronze disease or localised chloride corrosion Manufacture evidence Mould		√
Colour, geometry and texture	Formation of corrosion products Salts efflorescence Soiling		√

5.6 Conclusions

Considering the above, the conclusion that virtual analysis cannot substitute for conventional one can be affirmed, however the combination of virtual and conventional methods can assure the best results. Visual assessment of PG models and RTI visualizations is recommended as a complementary method, but it can't be a panacea, because there are features that cannot be visualised effectively. For that reason, other methods than the visual should be employed. Of course, knowledge of the nature of the environment and the composition of the material can also assist in this virtual exploration.

5.6.1 RTI's contribution to conservation

Application of RTI in artefacts derived from the Derveni tombs leads to better understood and more advanced documentation of depositions and encrustations, physical damage, inscriptions and engravings, impressions, decorative elements, wear evidence, surface features, working, manufacture or fabrication evidence and previous treatment evidence. Based on the findings of the numismatics RTI research, the identification and dating, condition reporting, conservation documentation and cleaning monitoring are the areas where the application of RTI enhances the current research methodology of numismatics. The application of RTI in the study of painted surfaces, demonstrated by examples of painted wood panels, canvas paintings, wall-painted fragments and painted pottery underlined the usefulness of RTI in examination, recording, documentation and analysis of decay features and manufacture evidence. Complete RTI visualization, depending on the characteristics of the object, may include the following integrated RTI approaches:

- microscopic RTI,
- normal RTI,
- reflected UV-RTI,
- UV induced visible fluorescence RTI,
- IR-RTI,
- trans illumination RTI and
- trans irradiation RTI.

The microscopic RTI, captured either with the Highlight RTI method and preferably with a mini RTI dome, combines the advantages of close up photography and photomicrography with those of RTI. In that way, microscopic RTI made it possible to catalogue the shape and topography of the various components of artefacts at a microscopic scale. Microscopic RTI provides an improved way for assessing objects microscopically. This technological development, proposed in this thesis, is of particular importance for conservation practice. Before applying microscopic RTI technique, it is useful to examine the object using normal RTI so as to define the areas of interest and the magnification needed.

The enhanced view of the artefacts under examination, provided by RTI and multispectral imaging, was significantly improved by the implementation of IR-RTI and UV-RTI, where the texture and three dimensionality features of the inner or outer layer are highlighted. The synergy of RTI and IR and/or UV imaging, results in an enhanced methodology for non-destructive examination of antiquities and works of art, and leads to different views of excavated artefacts, as well as painted works of art, which can be used for documentation, presentation, communication and research purposes. This was demonstrated by case studies on painted surfaces, including archaeological materials and works of art. This research consists of the most in-depth study for the application of multispectral RTI in conservation practice presented so far in conservation literature. RTI visualization of Gnathia and Faenza maiolica ceramics, covering the whole spectrum, demonstrates the advantages of multispectral RTI instead of multispectral imaging. The contribution is briefly summarised in Table 20.

Table 20: The contribution of RTI methodologies in the examination of painted and glazed pottery

RTI METHODS	CONTRIBUTION
RTI	• Captures the texture of the surface • Emphasizing decoration elements and decay features
IR-RTI	• Penetrates outer surface layer and reveals a clear picture of the three dimensionality of the inner layer • Emphasizing manufacture evidence • Decoration patterns may be emphasized depending on materials' response to IR radiation
UV-RTI	• Emphasizes subtle variations in the outer layer that are not clear in the visible spectral area • Reveals episodes of the museum life of the artefact • Reveals manufacture evidence and decay relevant to varnish layer or glazes
MICRO-RTI	• Captures micro surface variation • Reveals manufacture evidence, decay features and decoration elements at a microscopic level

Transmitted RTI's main potential is to document the structure of materials (paper, canvas), their condition (repairs, abrasions, losses) and painting techniques, and to reveal the texture of hidden features, obscured by linings, mounts or inks and pigments, such as under drawings, inscriptions and watermarks, assisting in that way in the perception of three-dimensionality, which is an issue of great importance for the characterization of materials, diagnostic examination and visual analysis. Table 21 presents the basic points of interest for the application of RTI methodologies, and summarizes their contribution to the examination of canvas paintings and similar materials.

Table 21: The contribution of RTI methodologies in the examination of canvas paintings and similar materials

RTI METHODS	CONTRIBUTION
RTI	• Captures the texture of the surface. • Emphasizes the three dimensionality of the painting layer. • Captures the texture of the substrate and the preparatory drawing only when thin paint layers have been applied. • Useful in condition reporting for the detection of deformations and other imperfections due to chemical, physical or biological damage.
IR-RTI	• Captures the texture beneath the visible due to IR penetration ability. • Emphasizes the three dimensionality of the paint layer according to the response of the pigments in IR irradiation. • Captures the texture of the substrate and the preparatory drawing clearly. • Emphasizes hidden features. • Useful in condition reporting for the detection of deformations and other imperfections in the layer beneath the surface.
TRANS ILLUMINATION RTI	• Captures the texture of the substrate and the variability of the paint layer. • Emphasizes areas of an increased translucency. Reveal s painting techniques. • Captures the preparatory drawing in when thin paint layers have been applied. • Useful in condition reporting for the detection of deformations and other imperfections, mainly mechanical shocks and physical damage, such as cracks, craquelere etc.
TRANS IRRADIATION RTI	• Captures the texture of the substrate and the preparatory drawing clearly. • Emphasizes the paint layer in case of pigments transparent or translucent in IR irradiation. • Useful in condition reporting for the detection of deformations and other imperfections, mainly mechanical shocks and physical damage, such as cracks, craquelere etc. • Successful in the detection of over painting.

RTI helps to explore the biographies of artefacts by enabling advanced examination of manufacture and use evidence, decay and conservation operations.

- Manufacture evidence: The study of the surface morphology reveals important evidence of the technology of manufacture used by our ancestors, which is hard to see under normal light, because of low relief and deterioration effects.
- Use evidence: In addition, identifying use evidence on artefacts is the most rigorous part of an examination, either because some objects have had only burial use or because decay patterns and/or conservation operations, such as cleaning, have covered and eliminated signs of use. It is a challenge for conservators to identify use evidence, often critical for the interpretation of the object.
- Decay: RTI's ability to emphasize surface variation can enhance visual analysis and offer advanced condition reporting
- Conservation operations: RTI can be used in order to examine the conservation state of previous repairs, as restored areas more or less present differentiations in texture, easily captured with RTI. Deficiencies, loss of cohesion and other reconstruction failure phenomena of the filling or/and the original object, hardly seen with the naked eye, appear more clearly with RTI.

Considering the objectives of a conservation project RTI can contribute significantly to: prevention, investigation, examination and analysis, documentation, communication, dissemination and presentation.

- Prevention: Due to the lack of preventive conservation measures, artefacts may rapidly age and degrade. Apart from the control of environmental conditions, mishandling is one of the factors of long-term deterioration, responsible for damage after excavation. In general, less handling of artefacts is recommended. RTI is considered a completely non-destructive technique, because it requires no physical contact with the original material. Its role as a preventive conservation measure is significant in cases of vulnerable artefacts in fragmentary condition and with a poor conservation state, because RTI visualization considerably

limits the amount of physical contact with the original material, while it delivers archaeological information more effectively than the artefact itself, and thus limits the risk of damage caused by handling.

- Investigation, examination and analysis: RTI is a useful tool for examination and analysis. Via normal, macroscopic, microscopic, reflected or transmitted visible and multispectral RTI, the observed phenomena, related to manufacture, use, decay and conservation, can be better understood, and hence lead to enhanced visual analysis either pre- or post-treatment. It reveals minor anomalies, scratches, gaps and pits, assisting physical damage examination and characterization. Decoration elements with low relief become apparent and are distinguished from depositions, encrustations or corrosion. Areas of different texture may indicate important archaeological material evidence, which will determine the interpretation of the object. Considering that the proposal of treatments is based on the interpretation and analysis of data provided by examination, the success of any conservation activity is strongly influenced by our ability to gather large amounts of high quality data.
- Documentation, communication, dissemination and presentation: RTI can substitute traditional documentation, mainly hand-drawings and photographs, which proved to be insufficient in the case of complicated artefacts, low relief details and reflective materials. It fulfils communication, dissemination and presentation needs, as RTI and PTM files can be published via the World Wide Web. In addition, the annotation tool, an outcome of the RTISAD project, which was further developed for the last release of the RTIViewer software, enhances scientific cooperation and online collaborative research.

The artefact visualised in RTI form is not just a static record of the artefact, but effectively facilitates virtual visual analysis without physical interaction, even if the physical artefact in the state it was visualised does not exist anymore, or has been altered due to human intervention or materials degradation. From the above it becomes apparent that RTI is a virtual examination tool, rather than just a recording technique.

5.6.2 PG's contribution to conservation

For the critical evaluation of the contribution of PG in conservation these primary objectives and actions should be considered.

- Accessibility-durability-integrity: 3D models are the most accessible format for a complete virtual artefacts examination. This is of particular importance in case of objects of extreme size and/or fragility. In these cases the virtual examination is proposed as the most appropriate method so as to ensure the durability and integrity of the object and avoid any damage due to handling. In addition, it is useful for remote areas when geographic constrains limit access to the archaeological material.
- Communication: Conservators can easily communicate conservation projects in the form of 3d models online, either between experts or to the public. In that sense, there is no doubt that scientific collaboration can be significantly enhanced.
- Practicality: The reconstruction of 3d models with PG is more practical than other 3d digitization methods.

PG and in particular integrated PG approaches can be useful for the investigation of artefacts as they combine the ability of multispectral and transmitted imaging to reveal features and the 3d artefacts inspection. This kind of visualization assists in appreciating the features revealed and their interpretation. In that sense it is not just a different presentation approach for transmittance and infrared data, but an investigation tool and a useful addition to the examination protocol. Application of microscopic PG can enhance the virtual examination of artefacts and is crucial for the application of the technique in conservation practice for recording, documentation, and conservation monitoring and treatment assessment. The preliminary results presented are promising. The equipment needed is common equipment used in conservation laboratories, and conservation professionals are familiar with its use. Moreover, considering that open source software is available for processing, it is highly likely that this technique can be widely used in the future. Moreover, the 3d digitization of an object at a particular stage of its lifetime, e.g. before cleaning or during the development of corrosion

phenomena, and the comparison with models created at different stages, can be useful in condition monitoring, conservation documentation and treatment assessment.

Nevertheless, the level of detail needed for conservation is far beyond the vast majority of 3d museum's online collections. The time needed for data capture and processing does not allow the photogrammetric reconstruction of large collections. As a result there is a need for the development of more straightforward approaches for capture and processing. There is an option to design special devices for data capture, in order to facilitate easier acquisition of high quality datasets. Moreover, the development of on time PG models would facilitate the broader application of the technique. Worth mentioning are the enhancement of surface detail on photogrammetry models by mapping RTI visualizations.

5.7 Summary

In the present chapter the application of digital techniques of RTI and PG for conservation recording and virtual visual analysis were considered. First, this chapter explored the synergy of H-RTI and optical microscopy, resulting to a prototype mini-dome suitable for micro- and macroscopic RTI capture. Second, potential use of multispectral RTI has been identified via the case studies presented. Third, synergies, not explored before, between RTI and FC as well as RTI and trans illumination and irradiation has been proposed and evaluated. Fourth, in terms of PG, different data capture strategies have been tested for lab 3d recording, including microscopic, infrared and transmitted PG. These novel applications and innovative uses of visualization technologies were applied to a broad variety of artefacts, evaluated and finally safe conclusions for their contribution in conservation were reached. Proposals for the enhancement of RTI and PG applications in conservation will be presented in Chapter 7.

In the following chapter the application of virtual and physical reconstruction using digital technologies will be discussed, with particular emphasis on fragments identification, replacement of lost material, de- and re-restoration dilemmas, in an attempt to identify the contribution of digital techniques in remedial treatment.

Chapter 6: Virtual and physical reconstruction

6.1 Introduction

The scope of this chapter is to evaluate the use of digital technologies in conservation treatment that promote conservation virtualization, which is the focus of this thesis. The operations that will be tested are fragments' identification (see section 2.2.2.2 for a discussion on fragments' identification problems), replacement of lost material (see section 2.2.2.3 for a discussion on gap filling problems) and re- de-conservation operations (see section 2.2.2.4 for a discussion on de- and re- restoration dilemmas). Particular emphasis has been devoted to these operations because of the potential of digital technology to contribute to the conservation workflow. Also, fragments' identification is one of the most common conservation operations that pose problems for conservators. The replacement of lost material is a controversial issue, and arguments about de- and re- conservation are well-known dilemmas in conservation. In addition to PG, RTI, in this chapter computed tomography, 3d modelling and 3d printing are employed. These techniques are being used for museum and archaeological research, but their application in solving conservation problems has been limited. The chapter is structured in three case studies, each of them devoted to a conservation operation; fragments' identification, replacement of lost material and re- de-restoration dilemma.

6.2 Fragments matching

6.2.1 Scope

The main goal of the experimentation on manual and digital semiautomatic fragments matching approaches is to compare the processes involved in these operations and correlate them to conservation objectives. Via this experimentation the common points, as well as the differences, between them can be understood, and offer an insight into the virtualization of digital fragments' identification.

6.2.2 Selection of study material and material evidence

Two similar late medieval North Italian Sgraffito jugs in Faenza Maiolica in a fragmentary state, with blue-ladder medallions, were used as a case study for the experimentation and comparison of manual and semi-automatic fragments matching. These vessels were selected because the degree of fragmentation is appropriate to provide insight into the process of fragments matching and concentrate on the methodological issues, which would have been impossible if a large number of fragments to be matched were considered. In the selected material the jugs are incomplete and the fragments are not well preserved, as demonstrated by the worn edges and the flaking-loss of decoration. The vast majority of the digital fragments matching approaches presented in the literature used archaeological material of an advanced degree of fragmentation as case studies (see section 2.3.2.3 for a literature review on digital refitting research and applications). This is understandable, considering that these studies had as their goal to test and demonstrate the efficiency of the new algorithms developed.

According to Brown (2002), both jugs, No 366 (Fabric 1450- SOU 124 176) and 367 (Fabric 1450- SOU 128 43) are late medieval maiolica, c. 1490-1510, probably from Faenza, with medallions on the front depicting piscine zoomorphic designs painted with blue and orange mineral pigments on a tin-glazed opaque background. Some fragments were joined, but most of the joins collapsed, as indicated by the remnants of adhesives on the edges. The 17 fragments attributed to the jug No 366 have been obviously cleaned. They comprise two fragments from the base, four fragments from the rim and several fragments of the body. In contrast the 29 fragments from jug No 367 were covered by encrustation and earth deposits, including 3 fragments from the base, 3 fragments from the rim, 2 from the handle and 21 from the body (Figures 347-349).

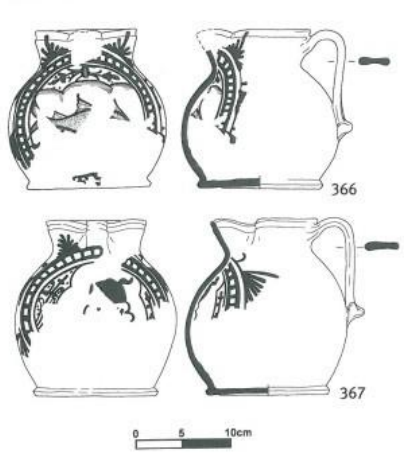


Figure 347: Drawing of the jug No 366 and 367 (Brown, 2002, p.72).

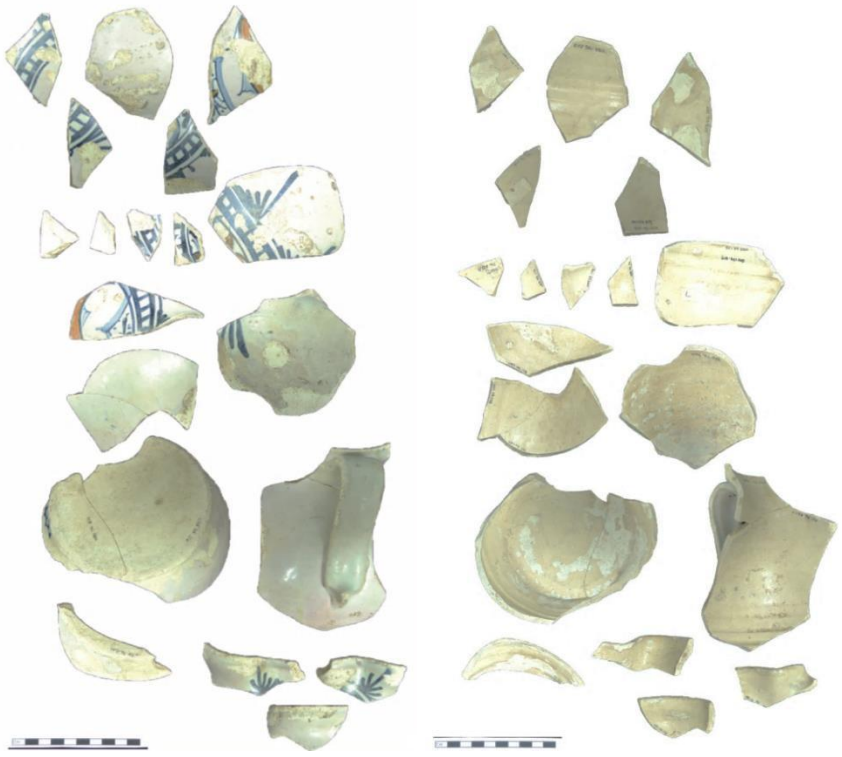


Figure 348: North Italian Sgraffito jug fragments in Faenza Maiolica with blue-ladder medallions No 366 (Fabric 1450- SOU 124 176), outside (left) and inside (right) from the Southampton city Council, Arts & Leisure (Image author's own).

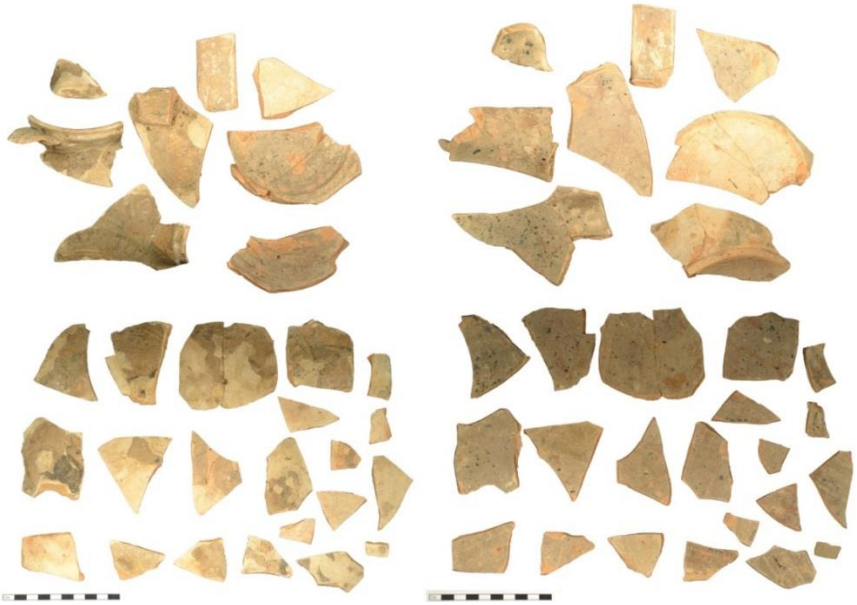


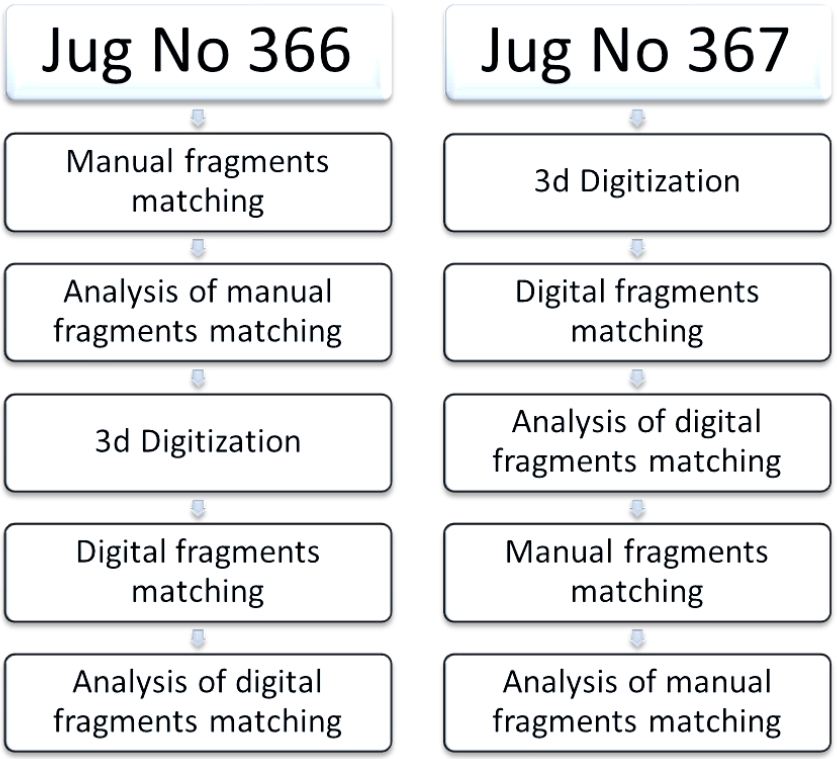
Figure 349: North Italian Sgraffito jug fragments in Faenza Maiolica No 367 (Fabric 1450- SOU 128 43), outside (left) and inside (right) from the Southampton city Council, Arts & Leisure (Image author's own).

6.2.3 Methodology

The two jugs selected are similar in terms of decoration and shape. All the fragments followed the same 3d digitization strategy. In order to enable an unbiased reconstruction the different approaches were applied in different times. The operation sequence is presented in Graph 40. For the jug No 366, the manual matching was followed by the digital. The manual fragments matching operation was video recorded and video transcripts have been produced in order not only to analyse the whole procedure and the individual actions that took place, but also to be used as guides for the digital fragments matching. The second phase of the experiment for the jug No 366, enables the analysis of the strengths and weak points of the available software for digital refitting. Of particular interest was their effectiveness in managing the project and correct alignment of fragments. For jug No 367, the digital fragments matching was executed first, followed by the manual. Lessons learned from the second phase of the reconstruction of jug No 366 are crucial for the semi-automatic digital refitting. In addition, other available options for the completion of the virtual reconstruction will be tested. The second phase of the

experimentation for jug No 367 consists of the manual fragments matching of the vessel and the evaluation of the results of the digital reconstruction.

Graph 40: Operation sequence for actions involved in the fragmented matching and digital refitting experimentation (Graph author's own).



6.2.4 Results and discussion

6.2.4.1 3d digitization

CT was chosen as the appropriate 3d digitization strategy for the purposes of the present experimentation, based on the material properties of the fragments. CT scanning not only succeeds in capturing the volume[57] but also offers the opportunity to study the internal structure of the ceramics (see section 3.4.1.2.2 for a discussion on CT applications on ceramics). The most

[57] See Digital Library, folder section6.2, folder SCC_UK_CER_FM366-DigitisedFragments for the digitised fragments of jug No 366 and folder SCC_UK_CER_FM367-DigitisedFragments for the digitised fragments of jug No 367.

interesting finding was the morphological study of the vessel's handle, which reveal a large void (Figures 350-351). This finding provides an insight into the manufacture and forming of the vessel. It would have been impossible to acquire this information non-destructively. In addition the CT scanned fragments can be rendered using volume rendering techniques that afford the opportunity to expose different parts of their volume, by modifying the opacity, as shown in Figure 352. The Phong renderer presents the object as solid. The isosurface presents the object as if the ceramic material is less dense, emphasising the volume of the glaze. The volume renderer scatter presents the glaze as if it is translucent. Details, such as the preservation of the glaze and cracks, can be examined in detail (Figures 353-354). Although the determination of composition and provenance goes beyond the scope of the present study, the capabilities of CT in this area of research should be noted. The reconstructed CT scan model can be further analysed in the future.

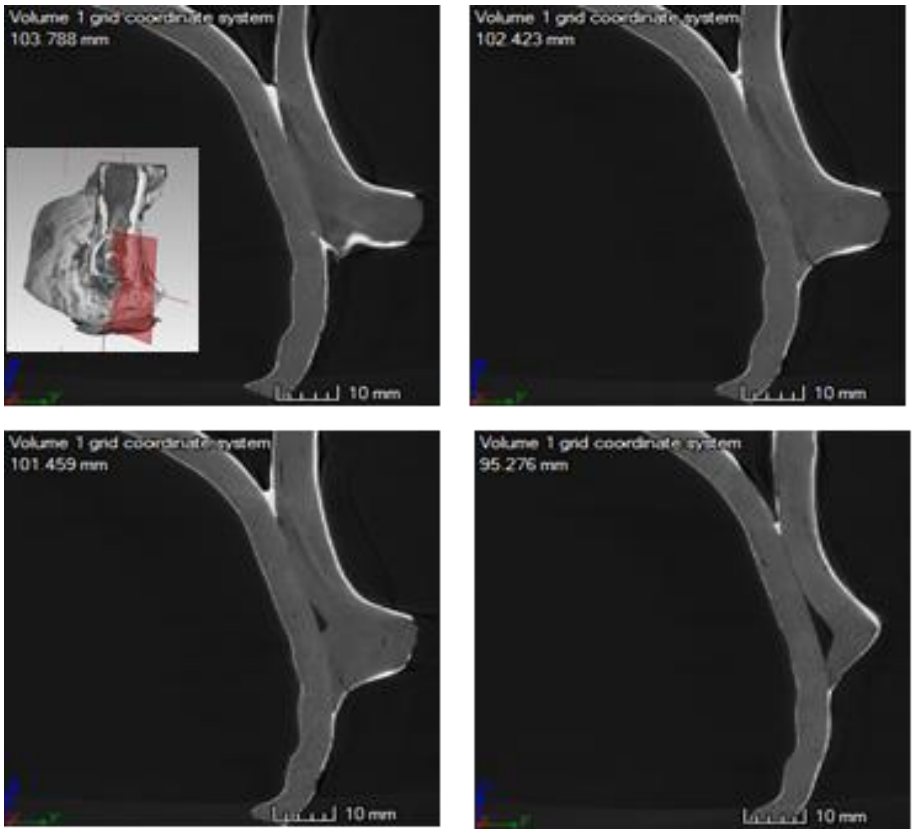


Figure 350: CT scan renderings for the handle of jug No 366, horizontal sections of the handle in VG Studio max (Image author's own).

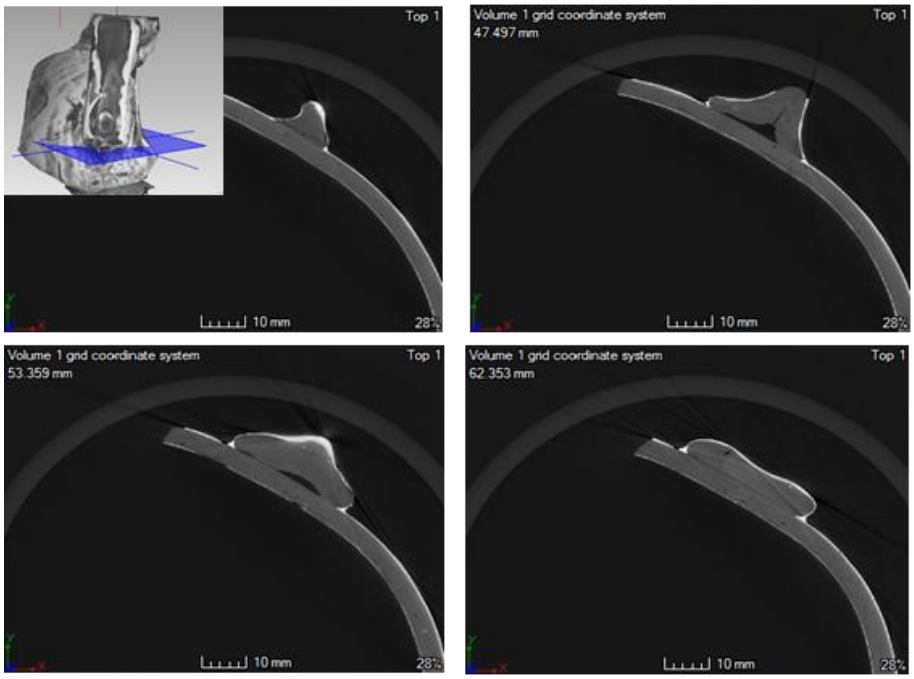


Figure 351: CT scan renderings for the handle of jug No 366, vertical sections of the handle in VG Studio max (Image author's own).

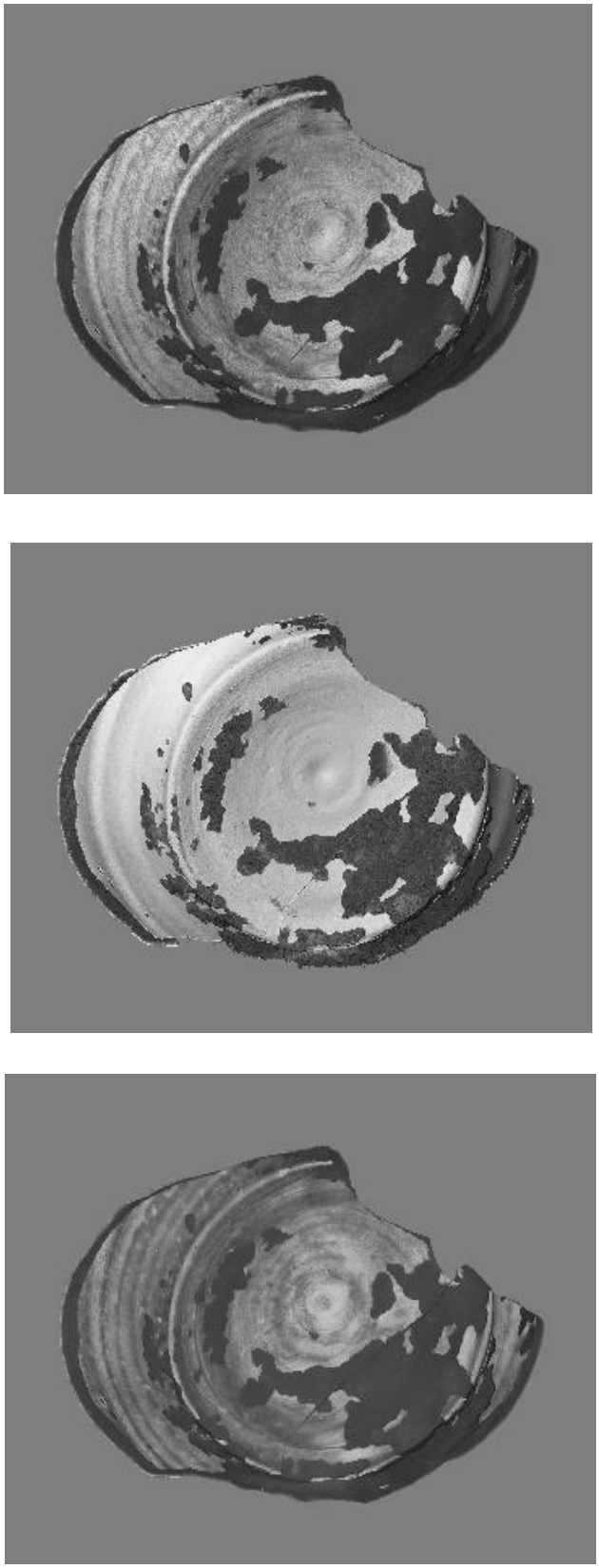


Figure 352: CT scanned fragment of the base of vessel 366,rendered using volume rendering techniques in VG Studio max, Phong (top), Isosurface (middle), Volume renderer scatter (below) (Image author's own).

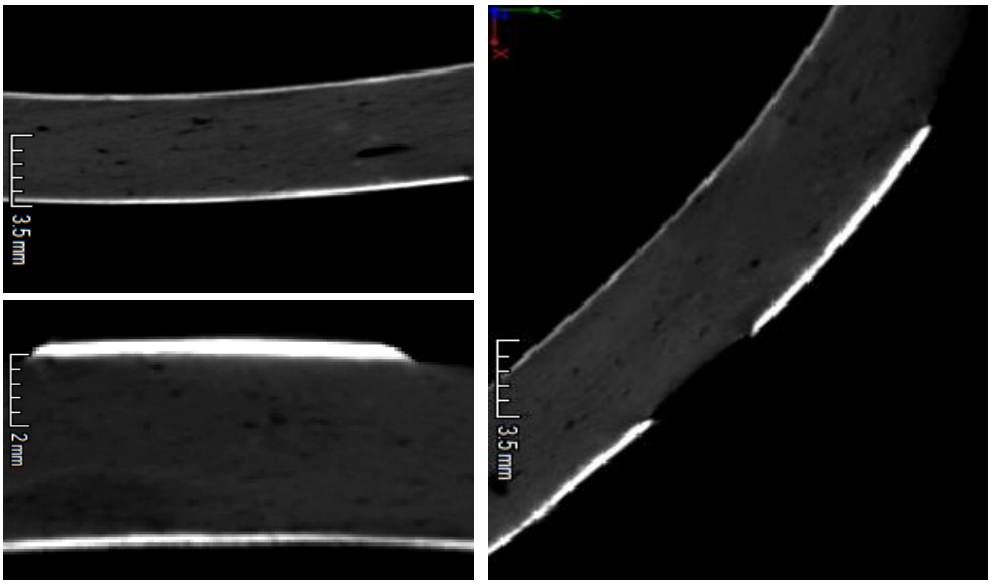


Figure 353: CT scanned fragment, visualizations of details showing the preservation of the glaze in VG Studio max (Image author's own).

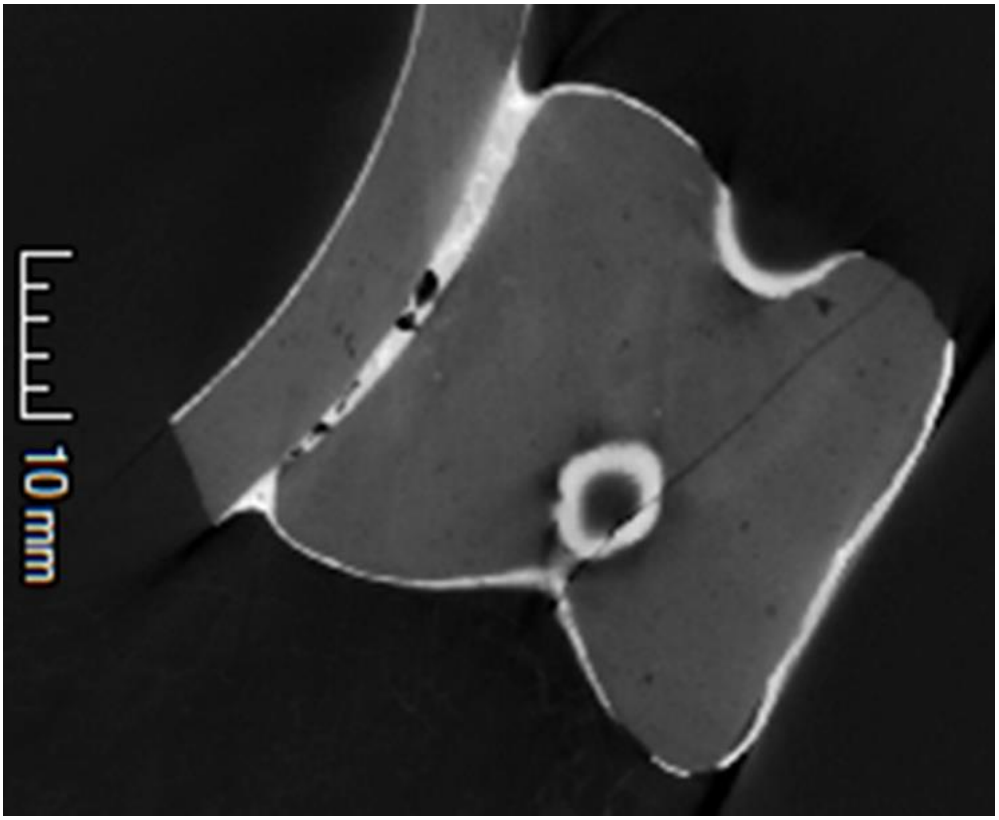
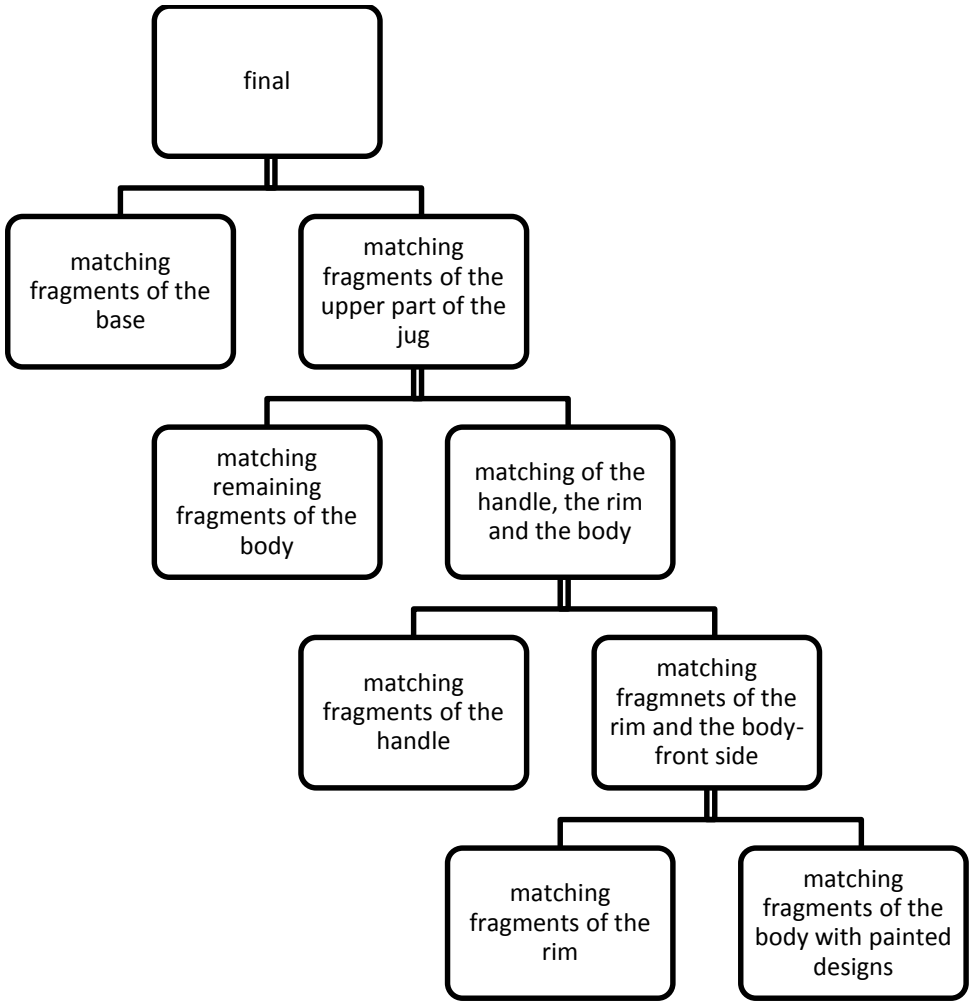


Figure 354: CT scanned fragment, detail showing cracks in the area of the handle in VG Studio max (Image author's own).

6.2.4.2 Jug No 366

6.2.4.2.1 Manual fragments matching

From the 17 shreds, attributed to jug No 366 only one remains unidentified and there is no doubt that it belongs to another pot. Fragments of the lower part of the body are missing as well as small fragments of the base and the rim. From the careful observation of the videos[58], transcript in excel was created which enable the quantitative analysis of the project (see Appendix C3). The Graph 41 presents a diagram for the reconstruction of jug 366.



Graph 41: The reconstruction process of the jug No 366 (Graph author's own).

[58] See Digital Library, folder section6.2, folder SCC_UK_CER_FM366_Manual, files Group_A.mov, Group_B.mov, Group_C.mov, Group_D.mov, Group_E.mov, Group_F.mov, Group_G.mov, Group_H.mov, Group_I.mov, Group_K.mov, Group_L-M.mov, Group_N.mov and Tests_2-R2.mov

The actions executed during manual fragments matching were the following: 1) observation, 2) selection of fragments with possible joins, 3) testing joins, 4) matching fragments and 5) securing joins temporarily. Figure 355 shows the execution of these actions in case of two fragments from the base. As shown in Graph 42 almost half of the actions involved in the project were relevant to testing for joins, while the occurrence of other actions is significantly lower. Along with instinct choices, the criteria used for manual fragments matching during the selection of the fragments were 1) the shape, 2) the painted design/ colour, 3) the texture and 4) the texture and shape (Figures 356-357). As shown in Graph 44, 60% of the successful matches were found based on shape, followed by 20% based on painted design. Other parameters lead to fewer matches and were mainly employed in case of repetitive unsuccessful tests. In Graph 44, the vertical axis represents the tests executed during searching for matches. The horizontal axis shows the criteria used. The red and blue bars depict tests resulting in successful and unsuccessful matches respectively. In both cases this comparison reveals that shape and painted design/colour were among the most frequently used criteria for searching joins, followed by shape and texture[59].

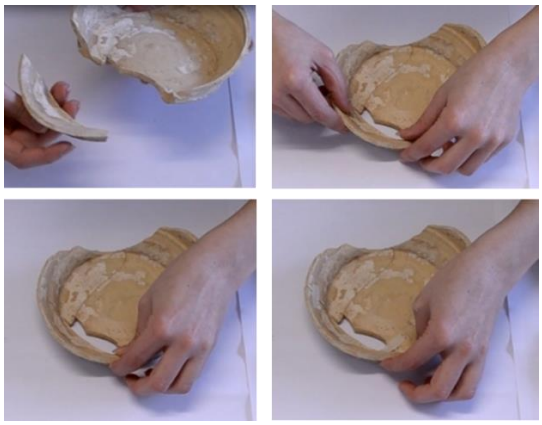
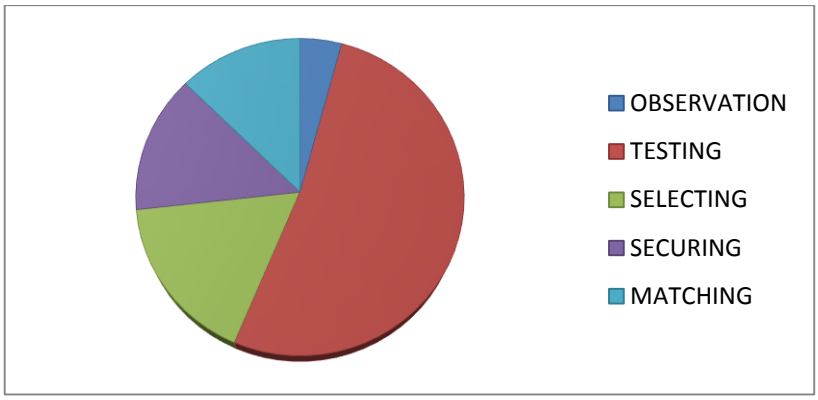


Figure 355: Details of still image from the video Group_A.mov, clock wise from top left, selection of fragments based on their shape (see frame 00:12), testing for joins (see frame 00:21), matching (see frame 00:26) and securing the join (see frame 00:41) (Image author's own).

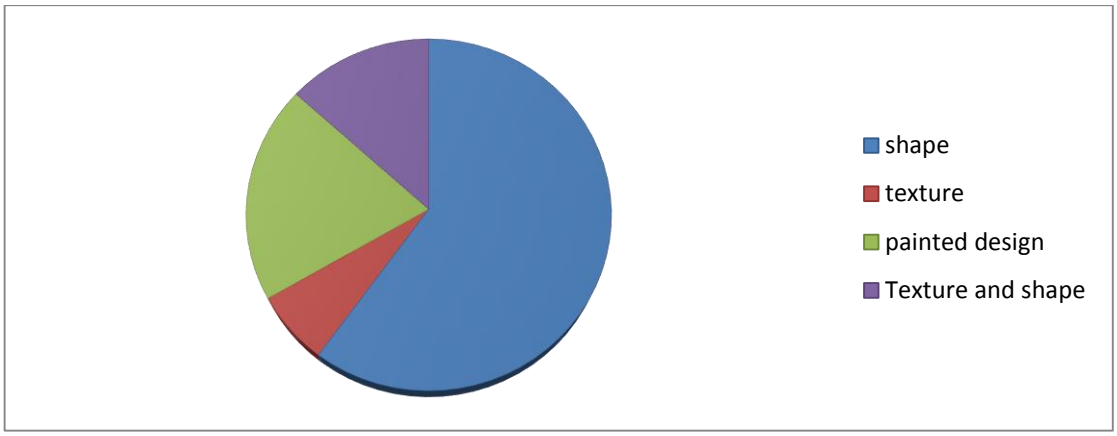
[59] See Digital Library, folder section6.2, folder SCC_UK_CER_FM366_Manual, file USS_UK_CER_FM366.xlsx



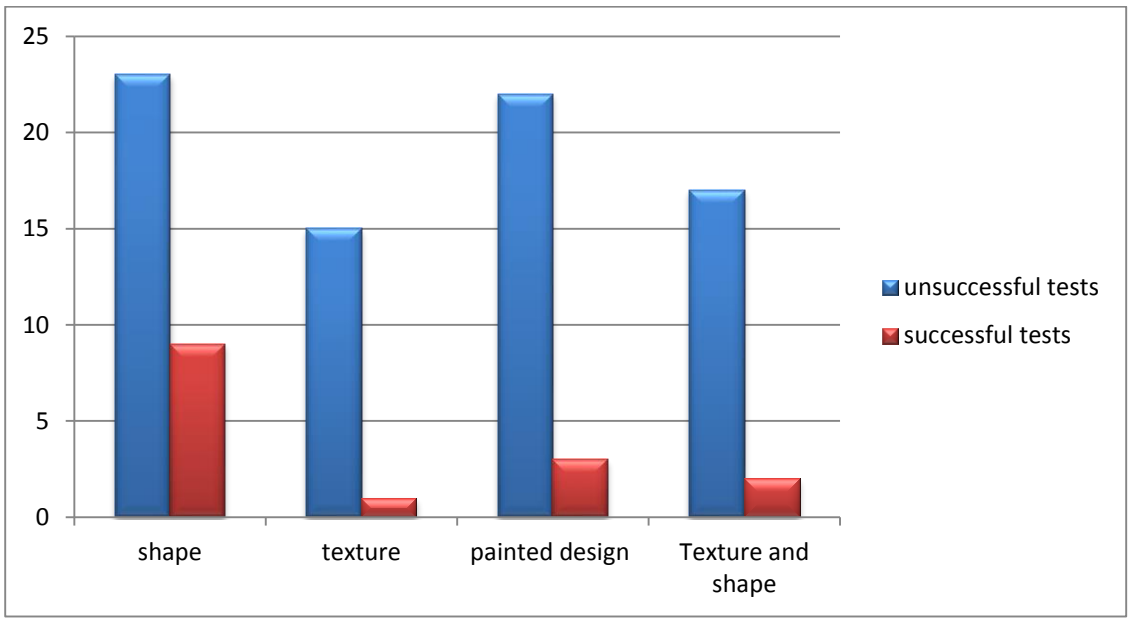
Graph 42: Occurrence of actions involved in the manual fragments' matching (Graph author's own).

Figure 356: Details of still image from video Group_B.mov. Testing fragments based on their colour/ painted design (see frame 1:02) (Image author's own).

Figure 357: Details of still image from video Group_I.mov. Testing fragments based on their texture (see frame 1:00) (Image author's own).



Graph 43: Contribution of each criterion in successful matching of fragments (Graph author's own).



Graph 44: Number of unsuccessful tests and successful matches for each criterion (Graph author's own).

6.2.4.2.2 Semiautomatic digital fragments matching

For the semiautomatic fragments matching of jug No 366 three different pieces of software, MeshLab (ISTI-CNR, 2014b), 3ds Max (Autodesk, 2014) and Fragments Reassembler (ISTI-CNR/3DCOFORM, 2014), were employed. Their effectiveness in managing the project and alignment of fragments will be examined.

6.2.4.2.2.1 MeshLab

MeshLab, developed at the Visual Computing Lab at the ISTI-CNR institute, is an advanced mesh processing system for automatic and user assisted editing, cleaning, filtering and converting and rendering of large unstructured 3D triangular meshes (ISTI-CNR, 2014a). The layer dialog enables managing the scene, where each fragment appears in its own layer and transformation matrix. The alignment process in MeshLab, originally developed for the alignment of laser scan data, uses the ICP (Iterated Closed Point) algorithm (ISTI-CNR 2014a). The user identifies one fragment of the fixed mesh as the base of the reconstruction and a second fragment as a moving mesh. At least 4 pairs of points, given by the user, provide the necessary information for the algorithm to find the best rigid transformation that bring the points of Moving mesh onto the corresponding points on the Fixed mesh (Figure 358).

Although, in theory, this process is feasible, and all fragments can be aligned successively over those already aligned, in practice this semiautomatic reconstruction operation is problematic. First, this process is not flexible. The user cannot modify the points of joins, and the procedure should be repeated from the beginning if a pair of points is given by mistake. Second, this method is inefficient in case of voids between fragments, whether they are larger or smaller. This is a significant disadvantage, particularly in cases of worn edges, which is almost always the case with archaeological fragments. Third, it is difficult to take into consideration the colour of the fragments and the painted designs, because the align tool does not enable the visualization of materials. Fourth, in the case of large number of fragments and/or high resolution meshes, the processing time becomes longer and technical problems arise. In order to overcome these problems, the best option is to create groups of fragments, flatten the meshes, export them as one file and proceed to the reconstruction having a significantly reduced number of fragments.

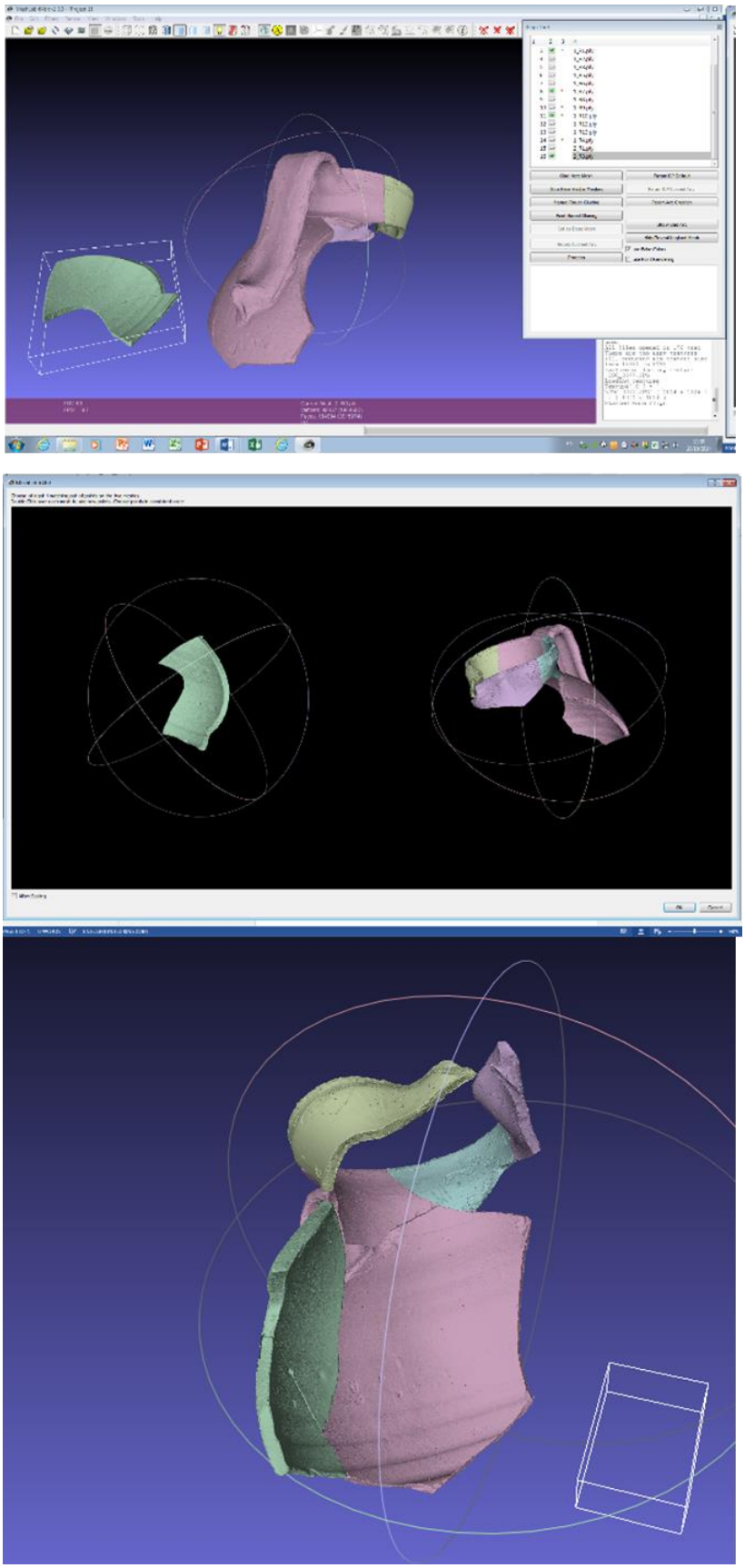


Figure 358: Using the align tool in MeshLab (Image author's own).

6.2.4.2.2.2 3ds Max

3ds Max is a powerful 3d design software which provides comprehensive modelling, animation, simulation and rendering solutions. Managing the digital refitting project, where each object in the scene represents a pottery sherd, is easy because of the use of summary statistics and scene explorer. These features display statistics and provide useful information about the current scene, meaning the number of objects, the total vertices and faces of mesh. The objects can be sorted in a list by category and object name, assigned material name, and type of material, object vertex and face counts. Further options for sorting, filtering, and selecting objects, as well as additional functionality for renaming, deleting, hiding, and freezing objects, as well as creating and modifying object hierarchies are provided by the Scene Explorer.

The alignment of the fragments using the available 3ds Max tool proved problematic. Precise positioning of a fragment relative to another is difficult. The options provided by max script offered advanced functionality in moving and rotating objects. In case of actions that have been already scripted, such as the arrangement according to size, max script proved to be particularly useful (Figure 359). The main disadvantage is that complicated actions, such as the matching of fragments, are difficult to execute because the necessary scripts are not developed yet. Even if the necessary resources for the development of scripts are available, it is difficult to script fragments matching, because this requires an advanced level of knowledge of the scripting language. In order to exploit all the available options an extensive search on the available scripts was completed. I have been unable to find any relevant scripts already developed.

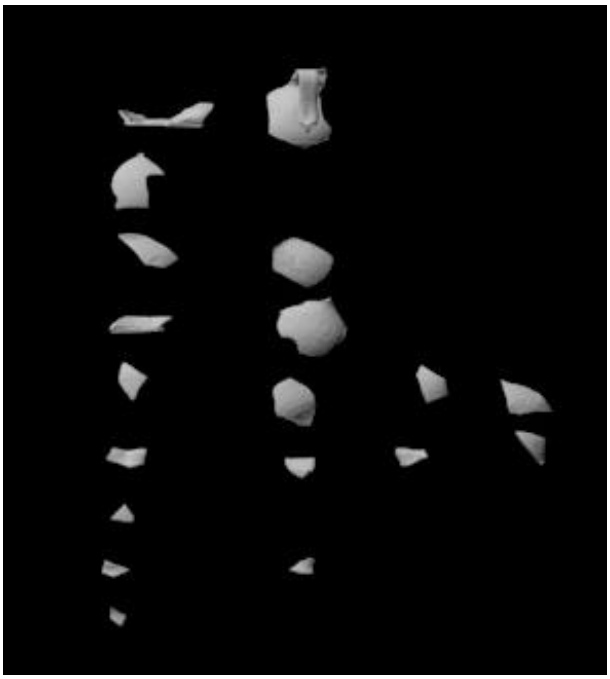


Figure 359: Alignment and distribution of fragments in 3ds max using max script (Image author's own).

6.2.4.2.2.3 Fragment Reassembler

Fragment Reassembler is a computer-assisted method for virtual reassembly of fragmented objects developed at Visual Computing Laboratory - ISTI – CNR. The software finds the best match between two fragments based on constraints given by the user, using a global energy minimization that considers all the pieces involved in the reconstruction process at once. It is based on a hierarchical system, where two fragments matched form a group, to which a third fragment or group of fragments can be attached. The user can move/transform the initial points, offering the opportunity to align fragments, even if they are severely damaged or eroded (Palmas *et al*., 2013). Among its disadvantages is the absence of efficient ways to manage the project, as well as practical problems usually occurring in the reconstruction process, mainly because the software is still in beta version, an early stage of development (Figure 360)[60].

[60] See Digital Library, folder section6.2, folder SCC_UK_CER_FM366_Semiautomatic

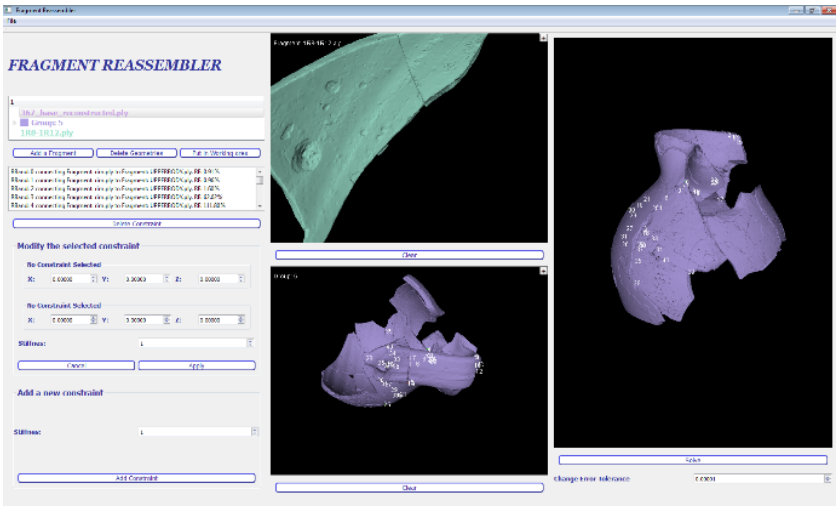


Figure 360: Using the Fragment Reassembler software, screenshot (Image author's own).

6.2.4.3 Jug No 367

6.2.4.3.1 Semiautomatic fragments matching

The lessons learned from the reconstruction of Jug No 366 were valuable for the semiautomatic fragments matching of jug No 367, whose fragments had not been identified manually. Hence, the digitised fragments were imported to 3ds Max, making use of the advanced option for managing the project and then the alignment were executed using Fragments Reassembler.

The 28 fragments attributed to jug No 367 were imported to 3ds Max (see Figure 361 for names assigned to digitised fragments), and using the measure utility the total volume was calculated. Then the volume was compared to the estimated volume of a complete pot of similar type, leading to the conclusion that almost 30 % of the vessel's volume is missing. By estimating the amount of missing material of the ceramic vessel, the conservator can gain a better understanding of the expected outcome of the reconstruction. The fragments were also grouped based on their shape using max script. This initial categorization concerns mainly larger fragments because these were more likely to be attributed to a specific type based on their shape. Based on this grouping the fragments were categorised in to five groups, three fragments

from the base, two fragments from the rim, two fragments of the handle, three fragments of the upper body and one fragment of the body (Table 22).

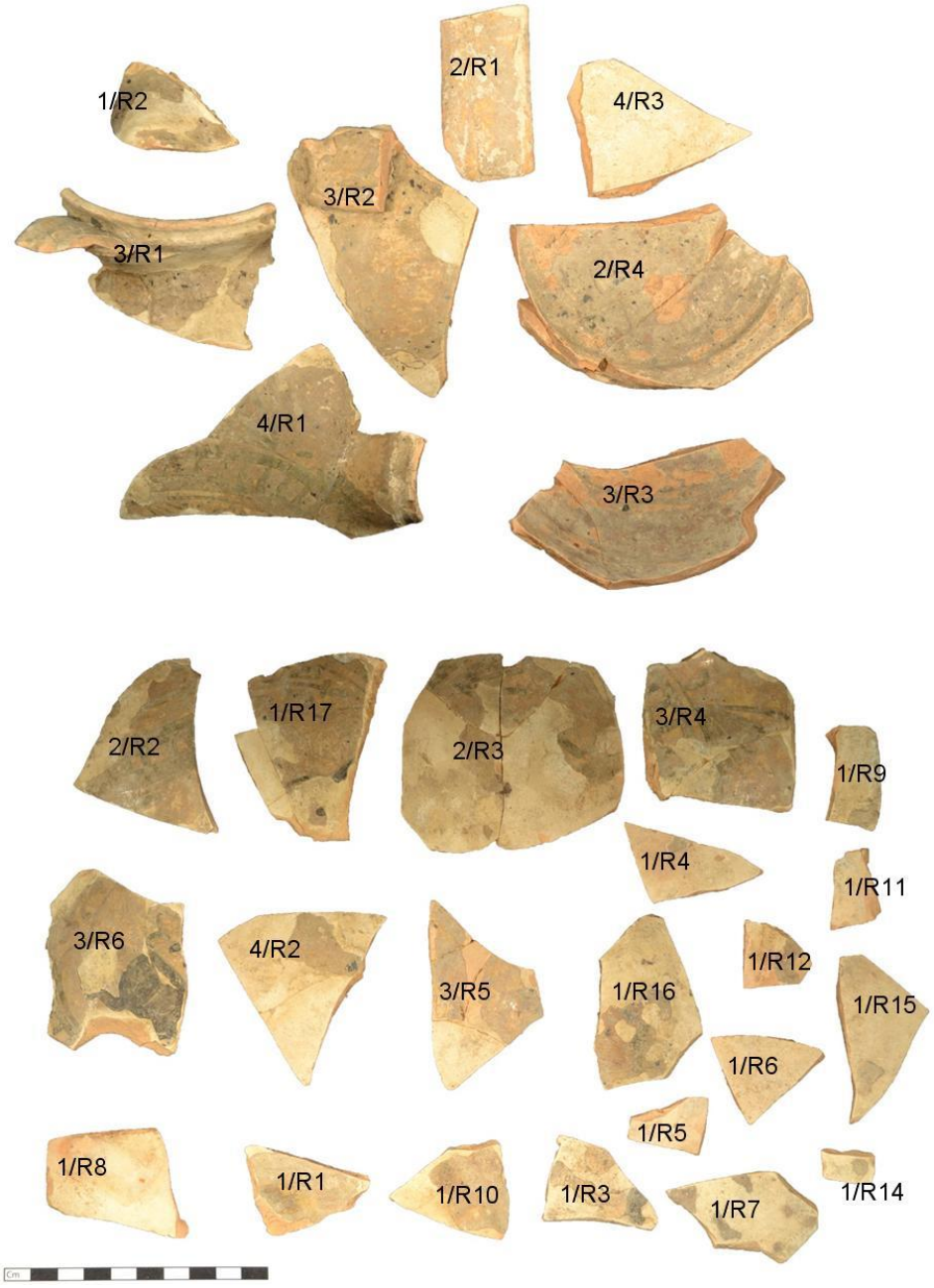
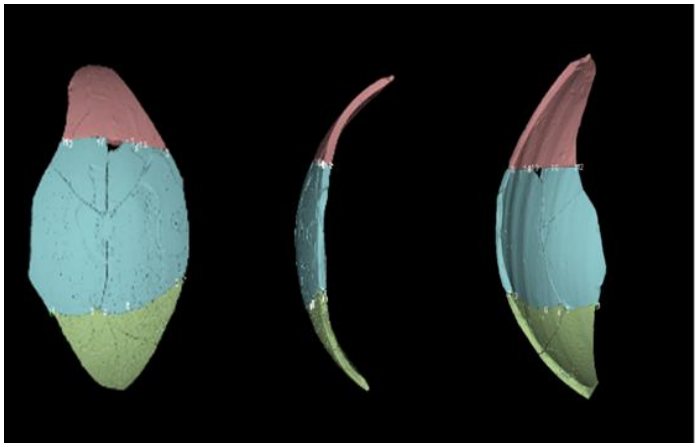


Figure 361: names assigned to each fragment of the jug No 367 (Image author's own).

Table 22: The fragments from Jug 367 listed according to their volume in metric units, and attributed to a specific type based on their shape.

Name	volume	description
367_2_R4	39209.72	base
367_3_R1	32322.59	rim
367_3_R2	30902.19	handle
367_3_R3	28381.16	base
367_4_R1	26569.53	rim
367_2_R3	24715.29	body
367_2_R1	15491.53	handle
367_3_R4	14674.85	upper body
367_3_R6	14243.9	upper body
367_1_R17	13697.6	upper body
367_4_R3	10656.04	base
367_2_R2	9235.91	body
367_4_R2	8801.76	body
367_3_R5	8061.05	body
367_1_R16	7839.36	body
367_1_R2	6815.4	rim
367_1_R8	6365.28	body
367_1_R10	5369.21	body
367_1_R15	5028.26	body
367_1_R1	4699.66	rim
367_1_R7	4668.8	body
367_1_R3	3501.84	body
367_1_R4	3386.9	body
367_1_R6	3154.76	body
367_1_R12	1794.13	body
367_1_R5	1733.35	body
367_1_R11	1523.22	body
367_1_R14	875.53	body

The selected fragments were aligned based on their geometry-shape, colour, and ceramic wheel marks leading to the construction of 5 groups; fragments of the body (Figure 362)[61], the base (Figure 363)[62], the rim (Figure 364)[63], the handle (Figure 365)[64] and the upper body (Figure 366)[65]. The alignment was executed in Fragments Reassembler. One of the remaining smaller fragments is part of the rim while the others were attributed to the body of the vessel. The virtual matching of these groups of joined fragments leads to the virtual reconstruction of the pot as shown in Figure 367 and in Graph 45[66]. The curvature and profile assisted the correct positioning of the remaining fragments. Finally, two fragments were not identified, probable due to their severely damaged edges. An Open Provenance Graph describes the process for semiautomatic fragments matching (Graph 46).



[61] See Digital Library, folder section6.2, folder SCC_UK_CER_FM367_Semiautomatic, files SCC_UK_CER_FM367_body_reconstructed.obj and SCC_UK_CER_FM367_body_reconstructed. aln
[62] See Digital Library, folder section6.2, folder SCC_UK_CER_FM367_Semiautomatic, files SCC_UK_CER_FM367_base_reconstructed.obj and SCC_UK_CER_FM367_base_reconstructed. aln
[63] See Digital Library, folder section6.2, folder SCC_UK_CER_FM367_Semiautomatic, files SCC_UK_CER_FM367_rim_reconstructed.obj and SCC_UK_CER_FM367_rim_reconstructed. aln
[64] See Digital Library, folder section6.2, folder SCC_UK_CER_FM367_Semiautomatic, files SCC_UK_CER_FM367_handle_reconstructed.obj and SCC_UK_CER_FM367_handle_reconstructed. aln
[65] See Digital Library, folder section6.2, folder SCC_UK_CER_FM367_Semiautomatic, files SCC_UK_CER_FM367_upperbody_reconstructed.obj and SCC_UK_CER_FM367_upperbody_reconstructed. aln
[66] See Digital Library, folder section6.2, folder SCC_UK_CER_FM367_Semiautomatic, files SCC_UK_CER_FM367.obj and SCC_UK_CER_FM367. aln

Figure 362: Parts of the body screenshot of Fragments Reassembler (Image author's own).

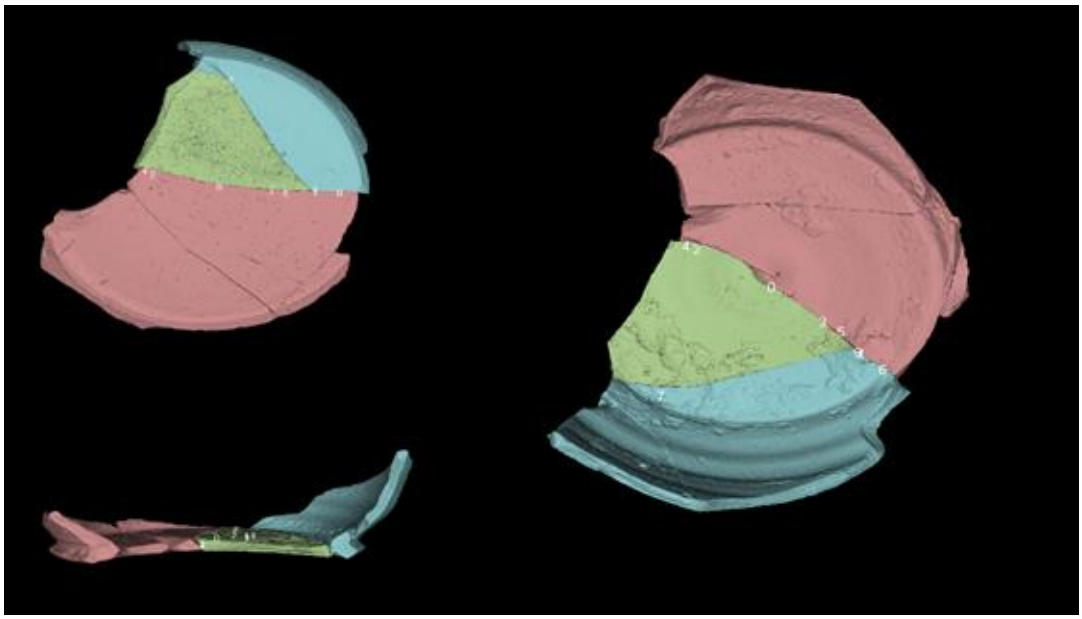


Figure 363: The parts of the base, screenshot of Fragments Reassembler (Image author's own).

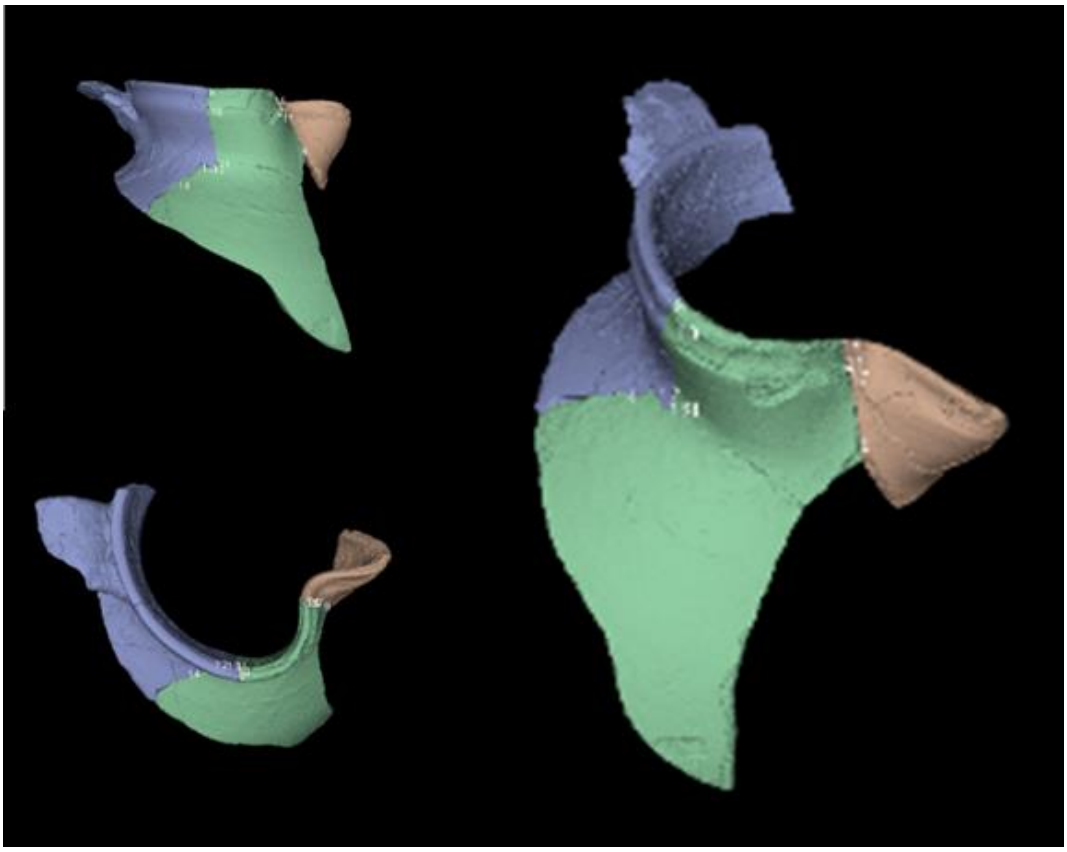


Figure 364: the parts of the rim (4R1, 3R1, 1R2) screenshot of Fragments Reassembler (Image author's own).

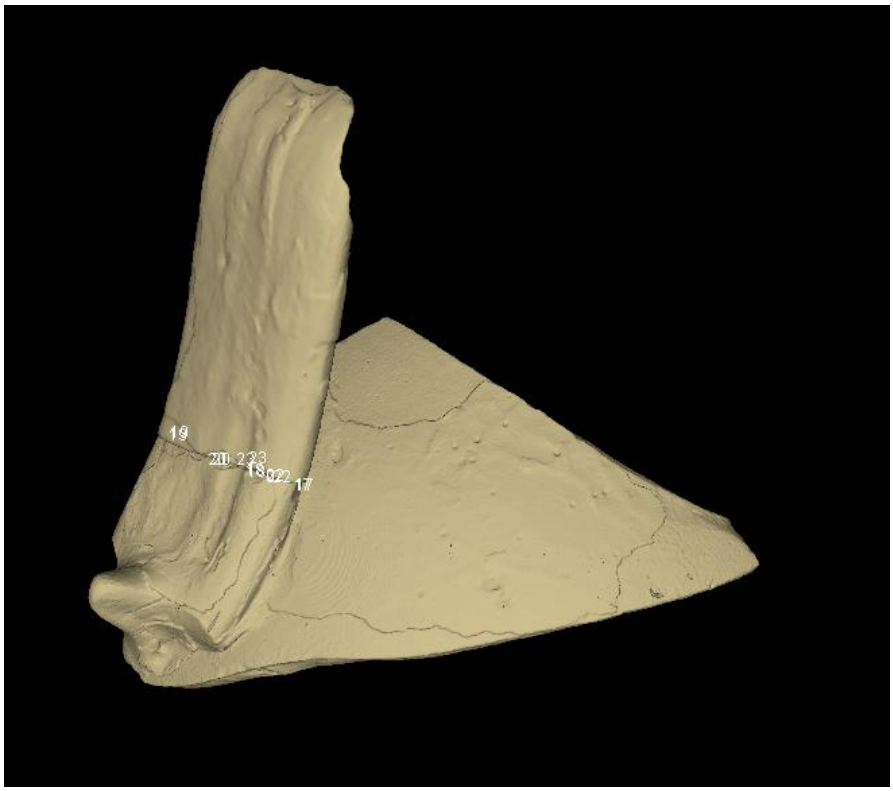


Figure 365: Parts of the handle (3R2, 2R1) screenshot of Fragments Reassembler (Image author's own).

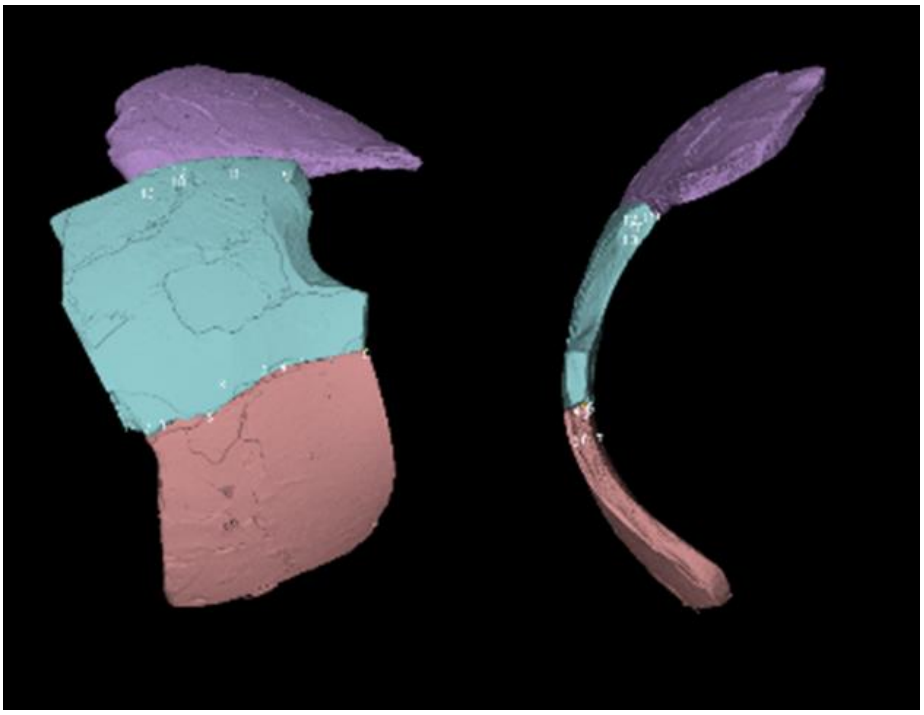


Figure 366: Part of the upper body screenshot of Fragments Reassembler (Image author's own).

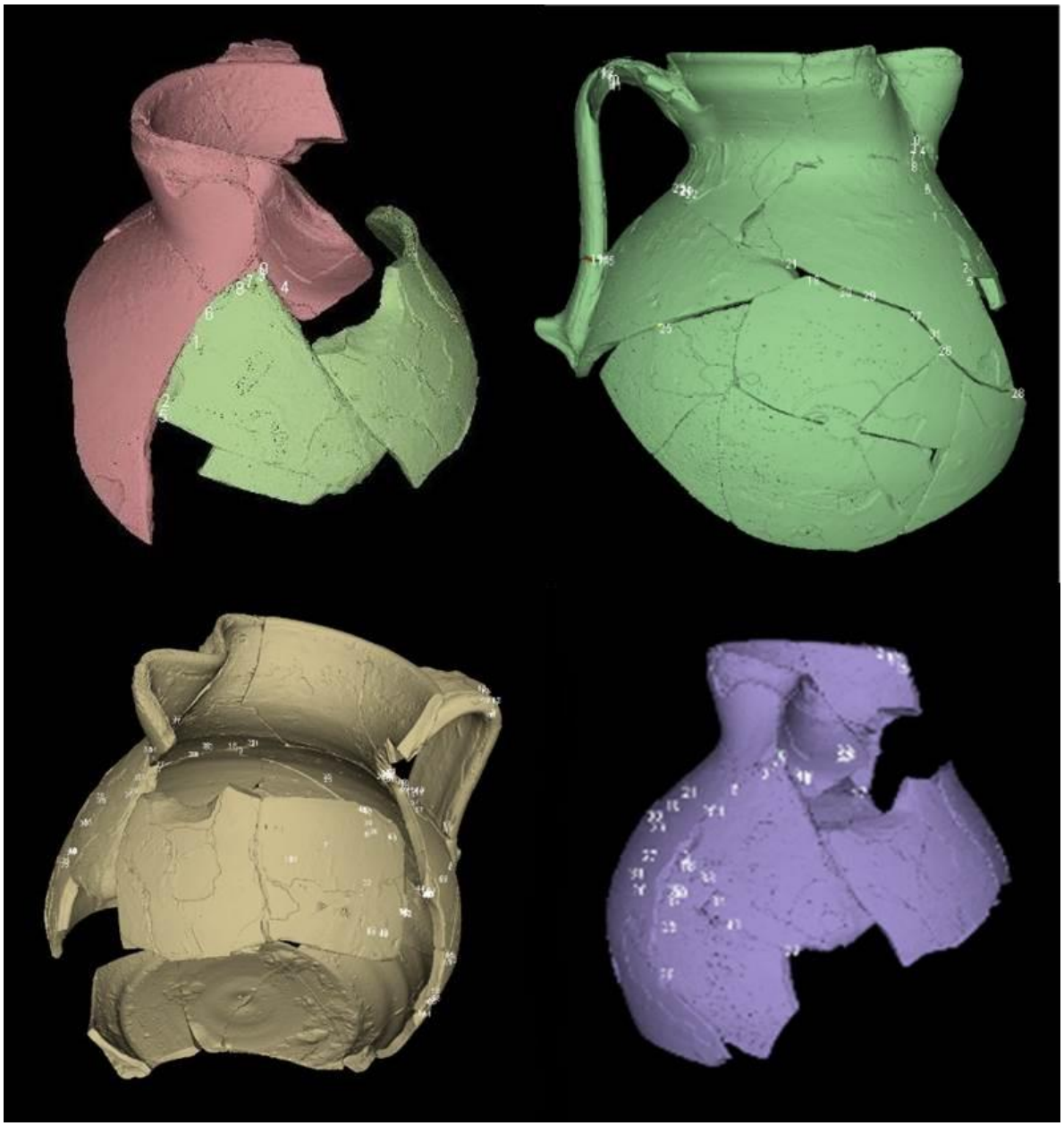
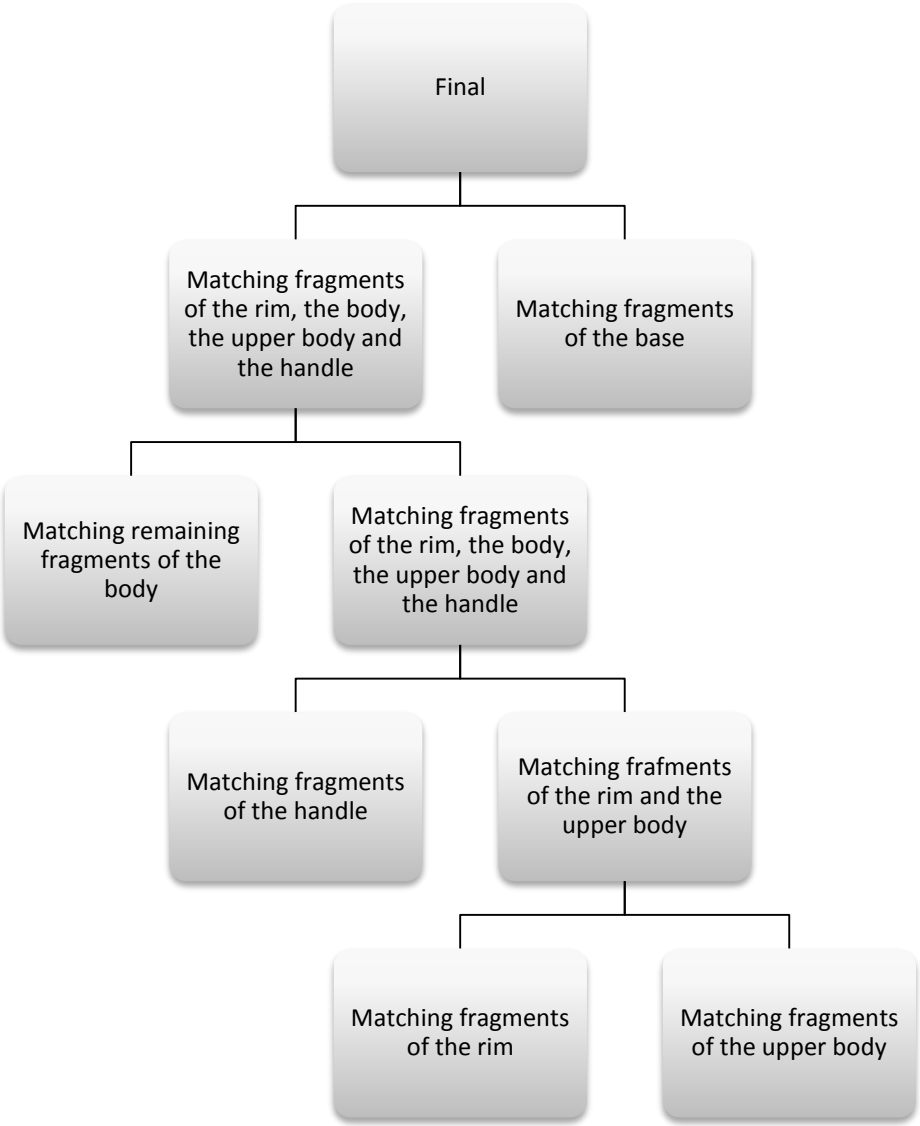
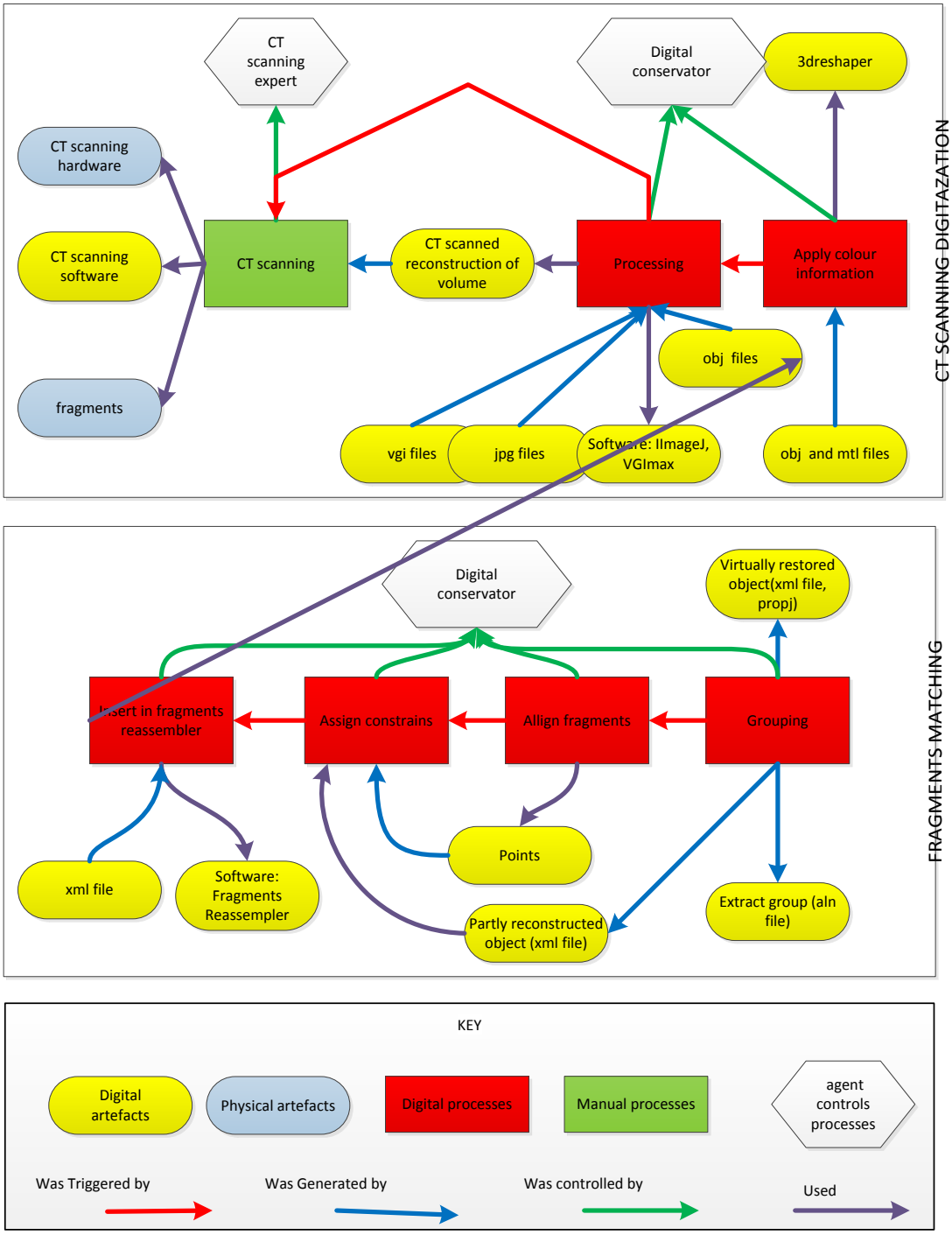


Figure 367: Virtual reassembly of the groups in Fragments Reassembler. Clockwise from top left, matching fragments of the rim and the upper body, matching fragments of the lower body, matching remaining fragments of the body and final reconstruction (Image author's own).



Graph 45: The reconstruction process of the jug No 367 (Graph author's own).



Graph 46: Open Provenance Graph for semiautomatic fragments matching (Graph author's own).

6.2.4.3.2 Manual fragments matching approaches

The findings of the virtual reconstruction were assessed physically following the traditional manual methodology, resulting in exactly the same fragments' identification. Due to the fact that the object has been already digitally restored, 3d modelling can assist the physical restoration in a number of ways. First, the digitally restored model can support the treatment proposal. Second, there is no need for extensive physical interaction with the fragments, considering that the exact positioning of each fragment is known. Third, using simple 3d modelling tools, a model of the inside of the object can be created and 3d printed in transparent material. This can act as a support for the positioning of the fragments, assist in the organisation of fragments and also allow the use of less quantity of adhesives for gluing. This is considered an advance digital alternative to the method proposed for the reconstruction of the glass beakers by Fisher and Norman (1987). Fourth, the missing parts can be modelled and 3d printed in an attempt to enhance the physical restoration of the object. This will be further examined in section 6.3.

6.2.5 Comparative analysis and evaluation

6.2.5.1 Semiautomatic fragments matching approaches

The comparative analysis of the three approaches assessed in the semiautomatic fragments matching of jug No 366 is summarised in Tables 23-24. 3ds Max is the most powerful software in terms of managing the project, because of the advanced options provided for selection, grouping and viewing the fragments. Similar capabilities, although with less functionality, exist in MeshLab. Fragments Reassembler proved to be the least useful in managing the project. For the alignment of fragments the tool specially developed for these operations, Fragments Reassembler, proved to be the most efficient. A similar result can be achieved using MeshLab, but the whole process is much more time consuming and limited to well-preserved fragments. It is highly unlikely to achieve the same or a similar result using 3ds Max, because of the limited functionality of the alignment tools provided. It is worth mentioning that MeshLab and Fragments Reassembler are open source while the 3ds max

software is commercial. Moreover, the advanced options provided by the latter require in-depth knowledge and familiarity with 3d software.

Table 23: Comparative analysis of software used for the semiautomatic digital refitting, based on the experimentation of the Jug No 366.

SOFTWARE	MANAGING THE PROJECT	ALIGNMENT OF FRAGMENTS
3ds Max	High functionality	Inefficient
MeshLab	Medium functionality	Medium efficiency
Fragments Reassembler	Low functionality	Efficient

Table 24: Advantages and disadvantages of the software tested, based on the experimentation of the Jug No 366.

SOFTWARE	Advantages	Disadvantages
3ds Max	Advanced options for managing the project Powerful tool for virtual reconstruction	Expensive Difficult to use Requires high computational power
MeshLab	Free Medium efficiency in aligning damaged fragments -Efficient in aligning well preserved fragments	Difficult to use for non-experienced users
Fragments Reassembler	Free Efficient in aligning fragments Easy to use	Limited functionality in managing the project Only useful for alignment In development stage-beta version-problems in use

6.2.5.2 Manual and semiautomatic fragments matching approaches

The fragments matching, as a core conservation operation, made the artefacts more accessible and understandable, whether it was executed physically or in a virtual environment, although the processes differ from a methodological perspective. An analysis of the semi-automatic and manual fragments matching reveals the parallels in terms of durability, integrity and practicality. There is an analogue here between the practical problems that arise in physical and virtual worlds. The problems of fragility and extreme dimensions have been discussed in the literature in cases of reconstruction of material in poor states of preservation, highly fragmented and/or large architectural parts. These problems govern the methodological approach and negatively influence the outcomes of the process. Although digital restoration provides a solution, the practicalities of digital refitting are similarly problematic. The computational power required for digital refitting of high resolution 3d digitised fragments, especially when a large number of fragments are considered, is high and slows down the process considerably. There is a need to compromise, reducing the resolution in order to overcome software and hardware constraints.

From a preventive conservation perspective the manual approach provides limited flexibility to the conservator. In particular complex reconstruction operations might cause risks to the material. Managing risks in interventive treatment is more demanding than managing the risks of 3d digitisation. In addition, the long-term structural and chemical integrity of the reconstructed object, compared to the digital preservation of the replica (either digital or physical-3d printed one), is more unpredictable. Hence, the digital reconstruction is advantageous from a strictly preservation or prevention point of view. Similarly, the digital approach is preferable for communication purposes. 3d models and audio-visual material from the digital execution of fragments matching operation can be disseminated easier for publication, documentation, training and outreach (Table 25).

Table 25: Correlation of problematic aspects of manual and digital fragments matching in terms of integrity, durability and practicality.

	Manual	Digital
Integrity	Intervention risks	Material digitization risks
Durability	Long term performance of reconstruction	Digital preservation
Practicality	Fragility, Extreme dimensions	Software and hardware constrains

6.3 Replacement of lost material

6.3.1 Scope

In this case study an alternative approach for the replacement of lost material incorporating 3d digitization, 3d modelling and 3d printing is presented. The goal of this experimentation is to evaluate the proposed methodology, considering that the application of virtual reconstruction using 3d printing has been applied to limited case studies focused on large objects and mainly without intending physical restoration. The virtual reconstructions presented in the literature never encountered the problems of aesthetic restoration. In this experimentation medium sized and fragile objects, whose restoration using traditional approaches is problematic, are used as case studies. Although the traditional methodology of '*the six-inches six-feet'* is widely used in museum conservation (see section 2.2.2.4), I have been unable to find examples of its applications in virtual reconstructions. This method can potentially enable us to define the appropriate properties of the filler. This experimentation also offers the opportunity to model the process of restoration.

6.3.2 Selection of study material

Incomplete bronze vessels are used as case studies for the virtual restoration and physical reconstruction. The restoration of the selected artefacts following traditional approaches is problematic due to aesthetic and practical reasons, because of the optical properties of the materials, their geometric complexity, the dimensions, the fragility and the poor preservation of the fragments.

Highly corroded bronze items in a fragmentary state from the Baughurst excavation, a Roman grave, were used as a case study. In particular the fragments are (Figures 368-372):

- two base fragments: a cast, hollow ribbed tube and an animal's head
- a handle with a female head at the base, possibly medusa and the upper part of a jug, with trefoil rim
- five highly corroded thin bronze sheets and
- miscellaneous small bronze finds.

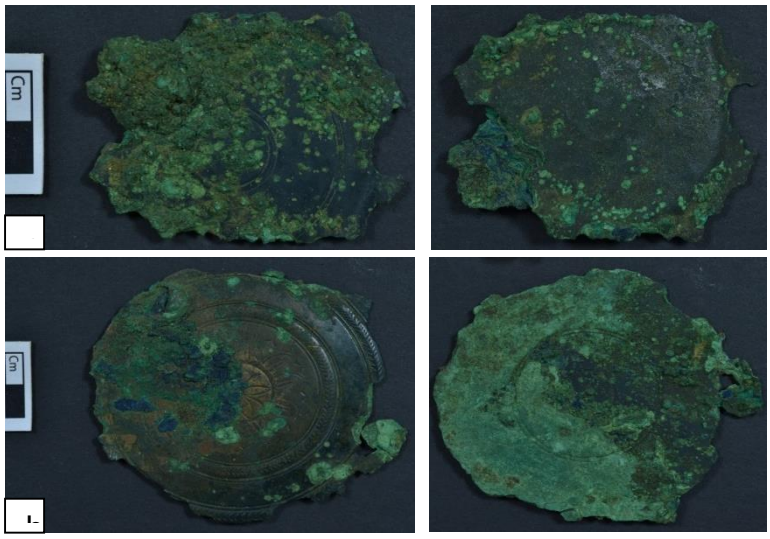


Figure 368: Base fragments. Hampshire Museums (Image author's own).

Figure 369: A cast bronze hollow ribbed tube and an animal's head. Hampshire Museums (Image author's own).

Figure 370: A handle with a female head at the base, possibly medusa (left) and the upper part of a jug with trefoil rim. Hampshire Museums (Image author's own).

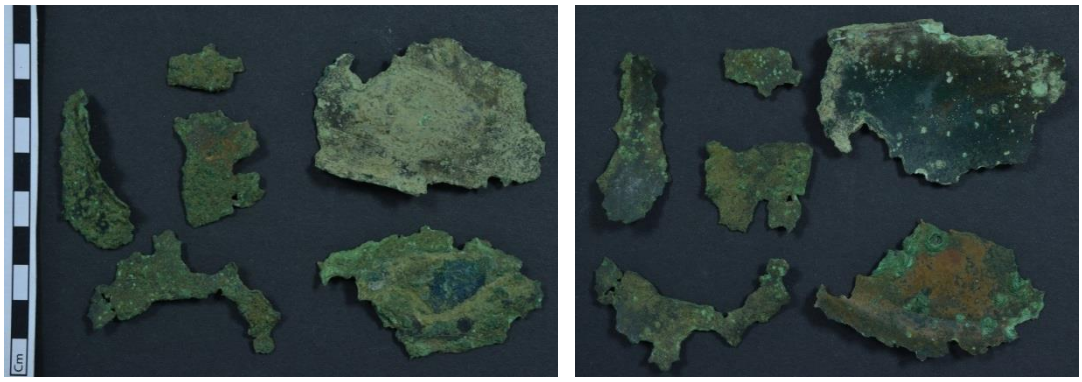


Figure 371: Highly corroded fragments. Hampshire Museums (Image author's own).

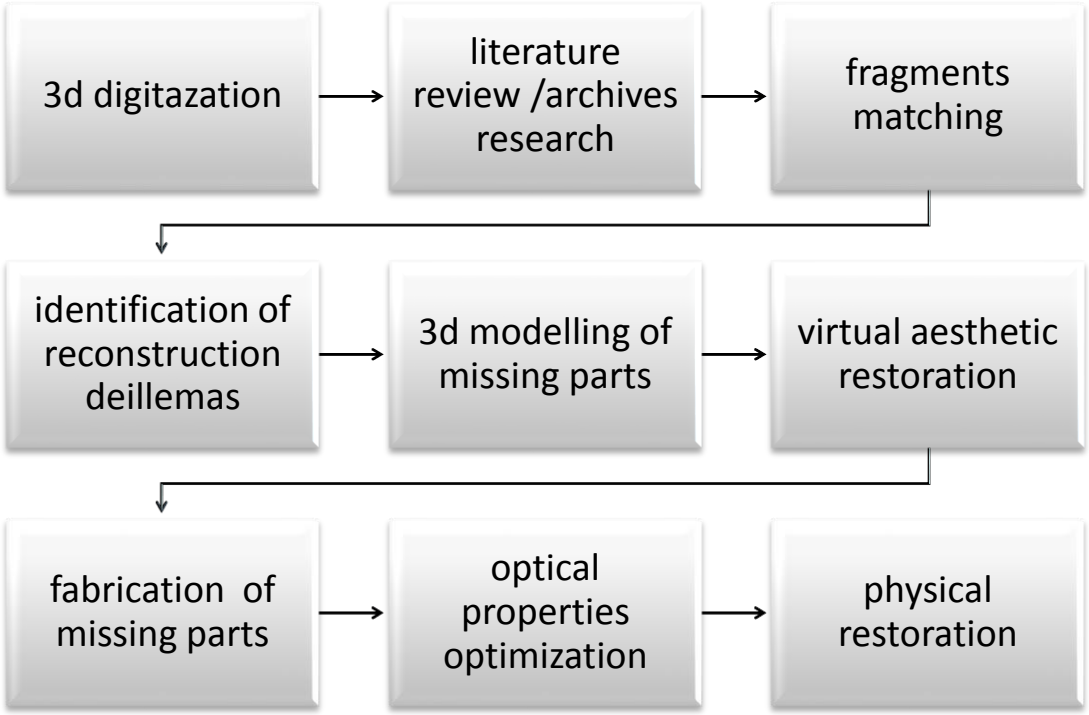
Figure 372: Miscellaneous fragments. Hampshire Museums (Image author's own).

From the surviving fragments an oinochoe (wine jug) with trefoil rim and a patera (a pan with a straight horizontal handle) can be identified with certainty. The two vessels for a group similar to the one discovered at Turner's Hall Farm, Wheathampstead, Hertfordshire, in March 2002 (Figure 373), as well as in Croatia and all over the Roman Empire. Although these objects are made for domestic use, the set of oinochoe - patera as a grave offering may suggest ritual significance (Jovanović 2010). The poor preservation state, the severe corrosion, the extended fragmentation and the large areas of loss make the correct alignment of the fragments and the physical restoration impossible following traditional methodologies. Three-dimensional modelling offers the possibility not only for safe manipulation and testing, avoiding physical handling, but also increased accuracy, which have been impossible in case of physical restoration.

Figure 373: Cast bronze Roman patera with a fluted handle terminating in a rams head and large cast bronze jug. From main burial one, one of two early 2nd century AD Romano-British burials discovered at Turner's Hall Farm. Available from: http://www.stalbansmuseums.org.uk

6.3.3 Methodology

The proposed alternative method incorporates the following steps, as shown in the Graph 47. The fragments of the vessels were 3d digitised, virtually joined and digitally restored via the modelling of the missing parts. Archives research and literature review are necessary so as to achieve evidence based reconstruction. The modelling of the missing fragments aims not only at the creation of detachable fills, but also the addition of features which can enable the safe position of the fills without the use of adhesive materials. The exact geometry and the ideal optical properties of the fill can be examined in detail and defined. A series of models was created in an attempt to identify which are the best optical properties of the fill. The models, when compared to each other, lead to conclusions regarding the most appropriate approach. The comparison will be based on the *6 inches 6 foot* rule.



Graph 47: The alternative restoration methodology proposed (Graph author's own).

6.3.4 Results and discussion

6.3.4.1 3d digitization

In order to acquire more information and detailed 3d models of the fragments, the CT scanning method was preferred (see section 3.4.1.2.3 for application of CT scanning on metals). CT scanning results in detailed 3d digitization of the fragments shown in Figures 374-375[67]. As well, CT enabled the study of the morphology and shape of the fragments, as indicated by the cross sections (Figures 376-379). The opportunity to study internal structures, and the available options in VG studio max to visualise variation in the metal material using pseudo colour volume rendering techniques, is also important. As shown in Figures 380-381, the formation of different copper oxides due to

[67] See Digital Library, folder section6.3, folder HMS_UK_COP_PATERA_DigitisedFragments

corrosion and cracking, indicative of the manufacture process (casting) are clearly observable.

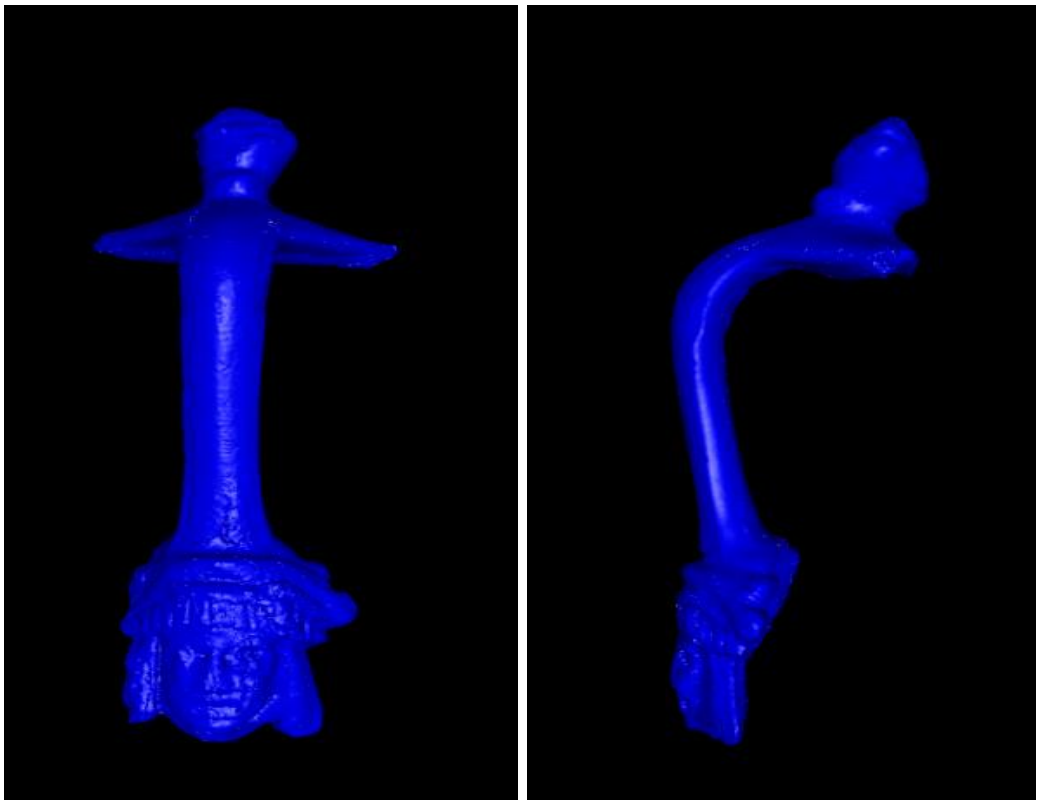


Figure 374: Renderings of the oinochoe handle in VG studio max (Image author's own).

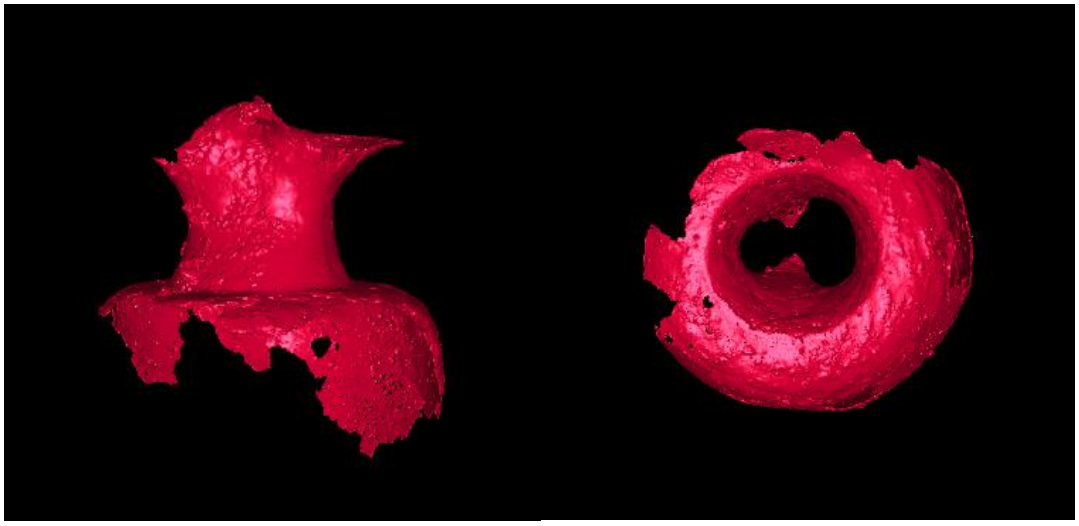


Figure 375: Renderings of the oinochoe body in VG studio max (Image author's own).

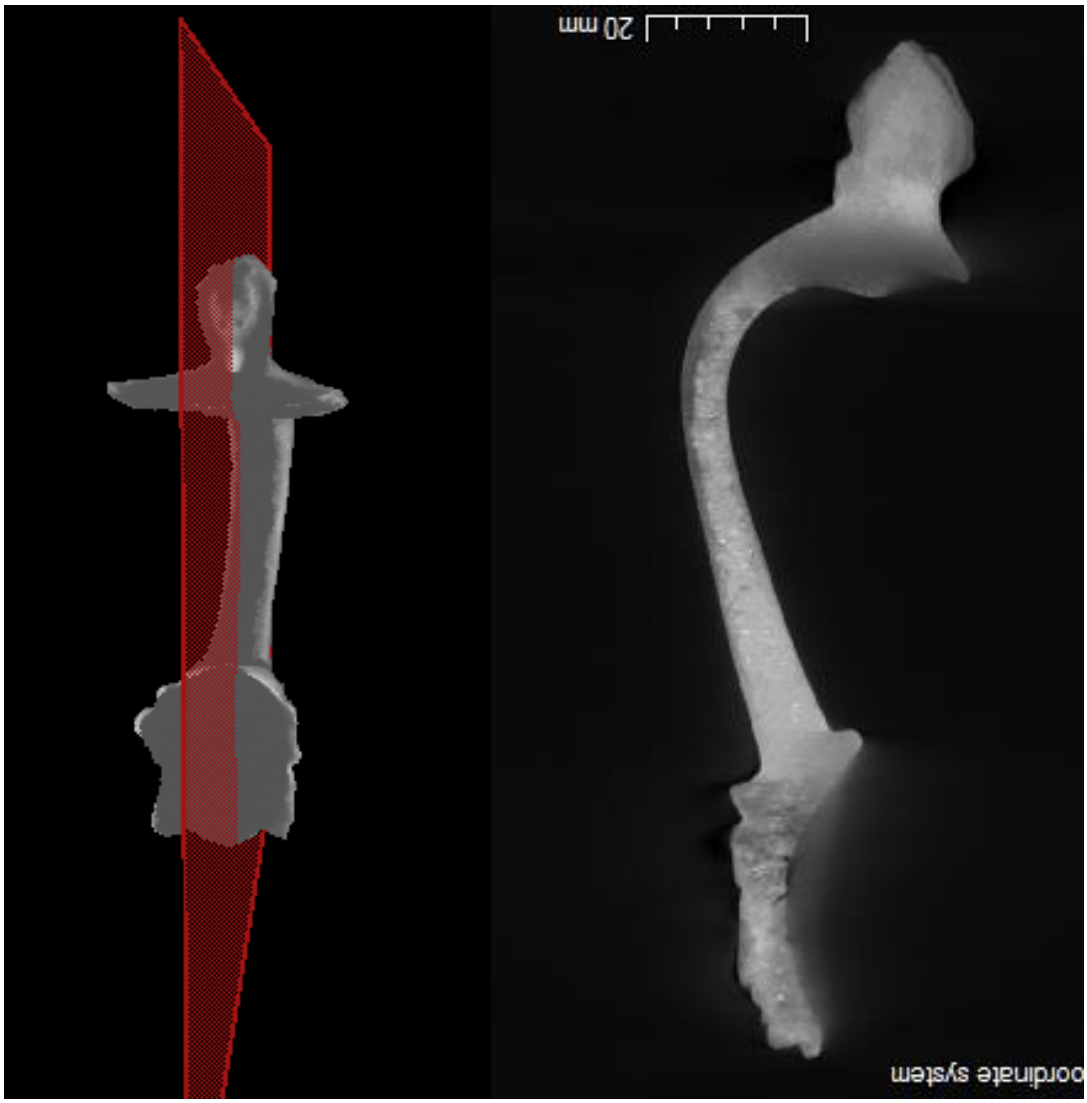


Figure 376: Sections of the oinochoe handle in VG studio max (Image author's own).

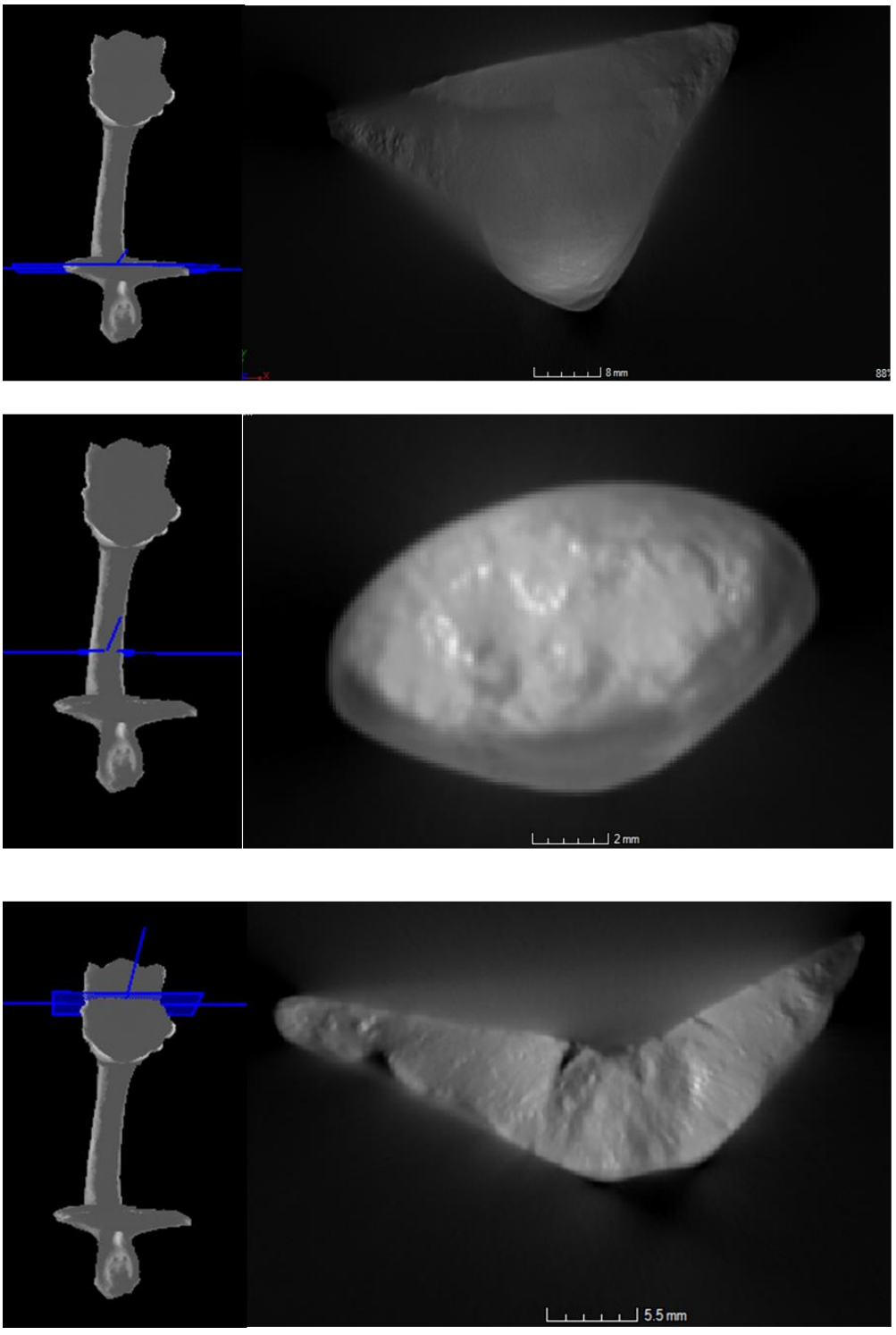


Figure 377: Sections of the oinochoe handle in VG studio max (Image author's own).

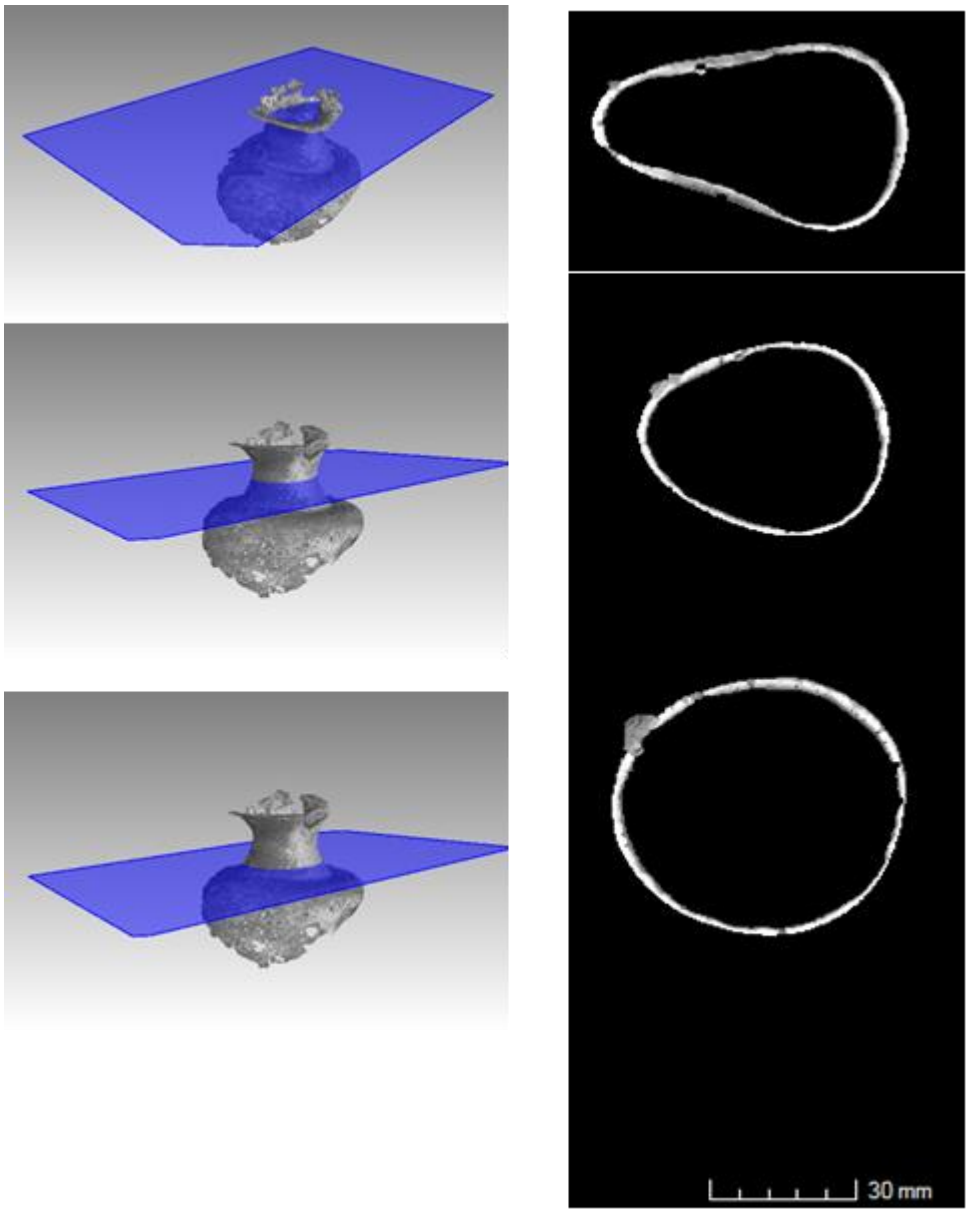


Figure 378: Sections of the oinochoe rim in VG studio max (Image author's own).

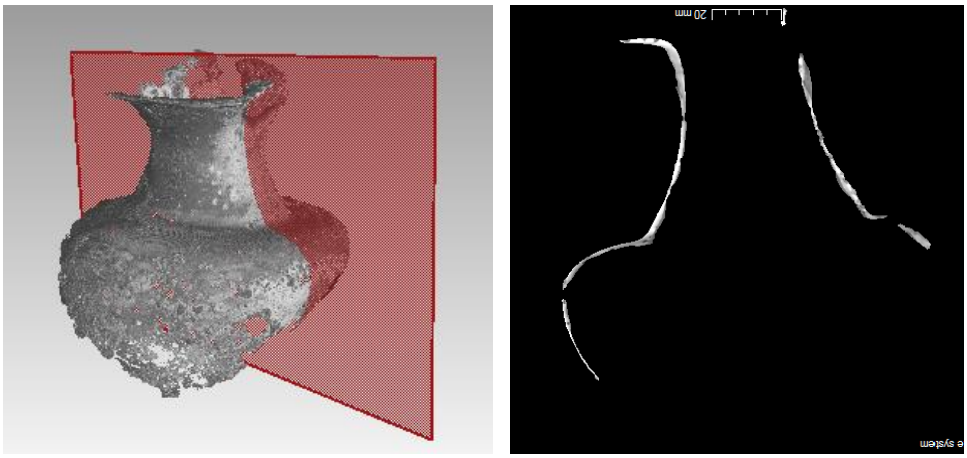


Figure 379: Sections of the oinochoe in VG studio max (Image author's own).

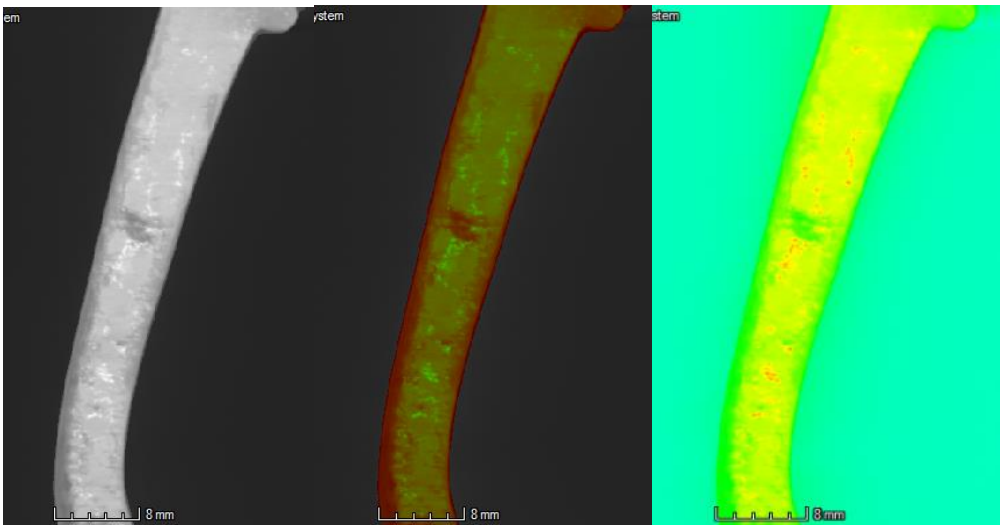


Figure 380: Comparison of different renderings in VG studio max (Image author's own).

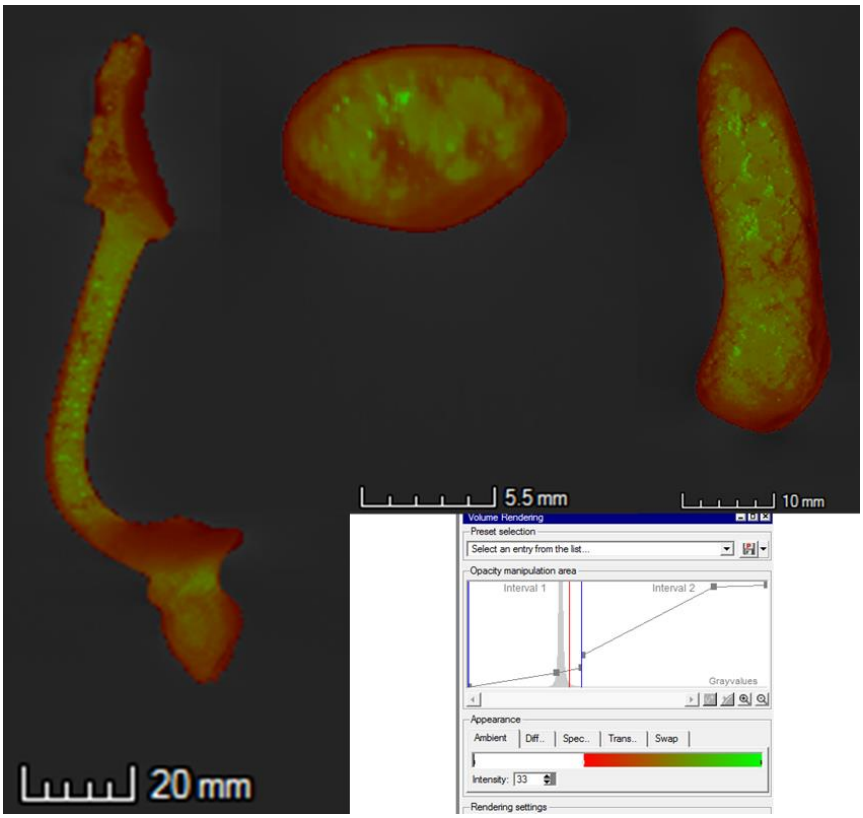


Figure 381: Colour rendering of the oinochoe handle in VG studio max (Image author's own).

6.3.4.2 Material evidence and typology

The shape and ornaments of handles provide important evidence for their typological categorization. From the surviving evidence the hollow ribbed tube and the animal's head terminal are attributed to the fine examples of shallow patera of Eggers types 154 or 155[68]. Similar examples of handles with ram's head terminals are presented in Figures 382-385. The vessel, based on complete similar examples and on Eggers typology, is a flat or umbilicus bottomed bowl without a foot-ring (Type 154) or with foot-ring Type (155). A variant of this type includes a ring fitted in front of the handle, fixed on the body by a soldered clip. Complete similar vessels are presented in Figures 386-390.

[68] Eggers, in his 1951 publication "Der Römische Import Im Freien Germanien", introduced a basic typology for patera with handles terminating at an animal's head. Dave Webb research is focused on refining a typology of different patera types (http://www.archdiggers.co.uk/Patera_Introduction.aspx).

Figure 382: Solid bronze patera handle terminating in a ram's head.1st C. length 12.6cm, diam. 1.7 cm. British Museum, Department of Greek and Roman antiquities, Museum number 1814,0704.907 Available from: http://www.britishmuseum.org/research.aspx

Figure 383: Hollow bronze patera handle terminating in a ram's head. 1st C. length 16.2cm, diam. 2.5 cm. British Museum, Department of Greek and Roman antiquities, Museum number 1814,0704.906 Available from: http://www.britishmuseum.org/research.aspx

Figure 384: Copper alloy patera handle. In form of ram's head from Hod Hill. Length: 15.6, diam. 2.2 cm. British Museum, Department of Britain, Europe and Prehistory, Museum number 1893,0601.472 Available from: http://www.britishmuseum.org/research.aspx

Figure 385: Cast bronze handle of patera with ram's head terminal from Bratislava-Devin, overall length 12.5cm (Kraskovska, 1978, p.49).

Figure 386: Cast bronze Roman patera and detail of ram's head handle terminal discovered at Turner's Hall Farm Wheathampstead, Hertfordshire, in March 2002. 44 BC - AD 400. Photo numbers PX1761 and PX1284 Available from: http://www.stalbansmuseums.org.uk

Figure 387: Bronze saucepan or shallow patera with a fluted handle terminating in a dog's head handle from Italy, Naples. Length: 34.9 centimetres. British Museum, Department of Greek and Roman antiquities, Museum number 1856,1226.700. Available from: http://www.britishmuseum.org/research.aspx

Figure 388: Bronze patera, early 1st century A.D. Length: 37.5 cm. Accession Number: 1989.281.87 Available from: http://www.metmuseum.org/collection

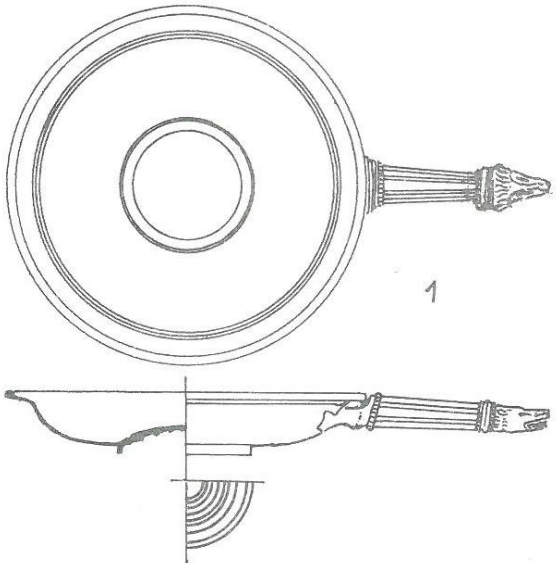


Figure 389: Shallow bronze sacrificial patera with horizontal handle and out-turned rim on a low foot-ring and with a central raised umbo bordered with concentric cycles. The handle terminates in a dog's head. Height 3.9cm, rim diameter 19.8 cm, base diameter 7.3cm, length of handle 13.8 cm. Eggers type 155 (Kraskovska, 1978, p. 75).

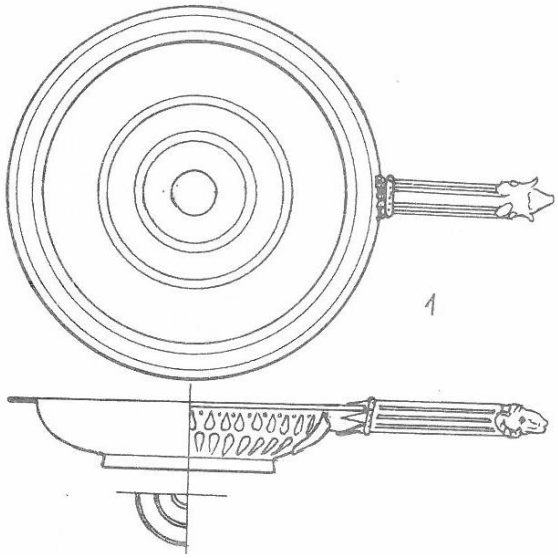


Figure 390: Shallow bronze sacrificial patera with horizontal handle and on a low foot-ring and with a umbo. The handle terminates in a ram's head. Rim diameter 25.8 cm, base diameter 12.5 cm, length of handle 12.1 cm. Eggers type 155 (Kraskovska, 1978, p. 78).

The second handle with the female head at its end is attributed to an oinochoe-jug with trefoil rim. This is probably a variant of an "oinochoe type 1" because of the distinctive trefoil mouth, but with a slightly elevated and curved handle instead of a high vertical one. This type is well known because of the large variety of the ceramic jugs surviving, which had their origins in bronze vessels. The body may be ovoid, globulous, and bulbous or of S shape profile. Similar examples from the British and the St Albans Museum are presented in Figures 391-394.

Figure 391: Bronze oinochoe with handle decorated with a figure of the wine-god Bacchus as a child (right). Height 17.78 cm. British Museum, Department of Greek and Roman antiquities, Museum number 1856,1226.656 Available from: http://www.britishmuseum.org/research.aspx

Figure 392: Small cast bronze Roman jug. There is a cow figure at the neck of the jug, and the handle terminates in a gorgon head. From burial two, one of two early 2nd century AD Romano-British burials discovered at Turner's Hall Farm. Available from: http://www.stalbansmuseums.org.uk

Figure 393: Large cast bronze Roman jug. The figure at the neck of the jug may be Silenus, a god of wine similar to Bacchus, a suitable choice for a wine jug. From main burial one, one of two early 2nd century AD Romano-British burials discovered at Turner's Hall Farm, Wheathampstead, Hertfordshire Photo number PX1103 PX1099 Available from: http://www.stalbansmuseums.org.uk

Figure 394: Bronze oinochoe with the handles terminating in a female head at the top and a satyr's mask on the body. 420BC-400BC. Ancient Greek. Height: 16.51 cm. British Museum, Department of Greek and Roman antiquities, Museum number 1884.0806.1. Available from: http://www.britishmuseum.org/research.aspx

The base fragment (fragment b) must come from the patera because of its decoration on both sides. It is highly likely for a base of an open shape vessel (patera) rather than a closed one to be decorated. Moreover, the other base fragment (fragment a), being plain from the one side and decorated with concentric cycles on the other side, is attributed to the oinochoe, as it resembles the one presented in Figure 395.

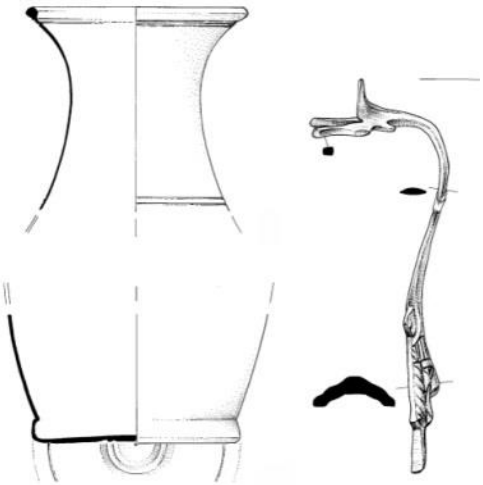


Figure 395: Polhov Gradec (SI), dépôt 2 [1883], c. 350/425, retrieved from the online encyclopaedia of small finds Available from: http://artefacts.mom.fr/en/home.php

From the miscellaneous small bronze finds the two mounts and the pelta foot are of particular interest. Evans has presented similar objects discovered at Clay Farm in Cambridge, as well as Feugère and Canny (Figures 396-397), and attributed them to the patera shape. A small pelta-shaped vessel foot with detached ends of articulated arms from the Archaeological Museum in Split, similar to the one under examination, is the foot of a trulla according to Jovanovic (2010), who associates the pelta-shaped feet with this specific vessel type. Kraskovska (1978) interprets a similar small find from Slovenia as a foot of a bucket, while similar feet have been associated with jugs attributed to a patera according to the Online Encyclopedia of Archaeological Small Finds (http://artefacts.mom.fr/en/home.php) (Figure 398).

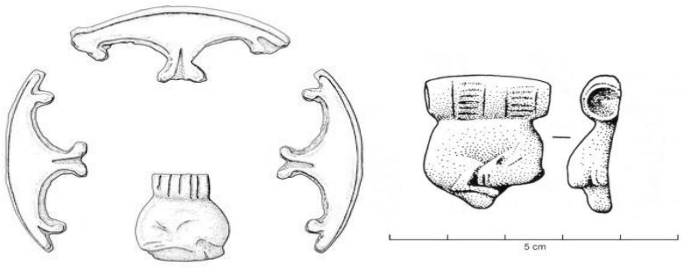


Figure 396: Bronze small finds attributed to a patera. Cambridge, Clay Farm (GB) (Evans 2008, p.164, pl.3.13) (left) and Villetelle, Ambrussum (34), applique isolée (Feugère 1986a, p.98, fig. 78, n°13)(right). Examples retrieved from the online encyclopaedia of small finds Available from: http://artefacts.mom.fr/en/home.php

Figure 397: Habitat rural, region (Canny) example retrieved from the online encyclopaedia of small finds (left) Available from: http://artefacts.mom.fr/en/home.php. Feet from bucket from Slovenia, length 6.6 cm, width 2.4 cm. (Kraskovska, 1973, p.63) (right).

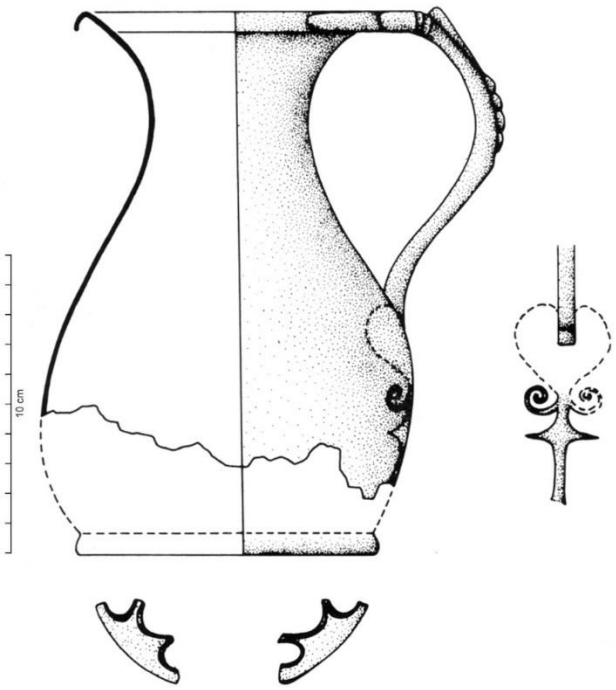


Figure 398: Bronze feet associated to jug shapes. Example retrieved from the online encyclopaedia of small finds Available from: http://artefacts.mom.fr/en/home.php

6.3.4.3 Reconstruction dilemmas

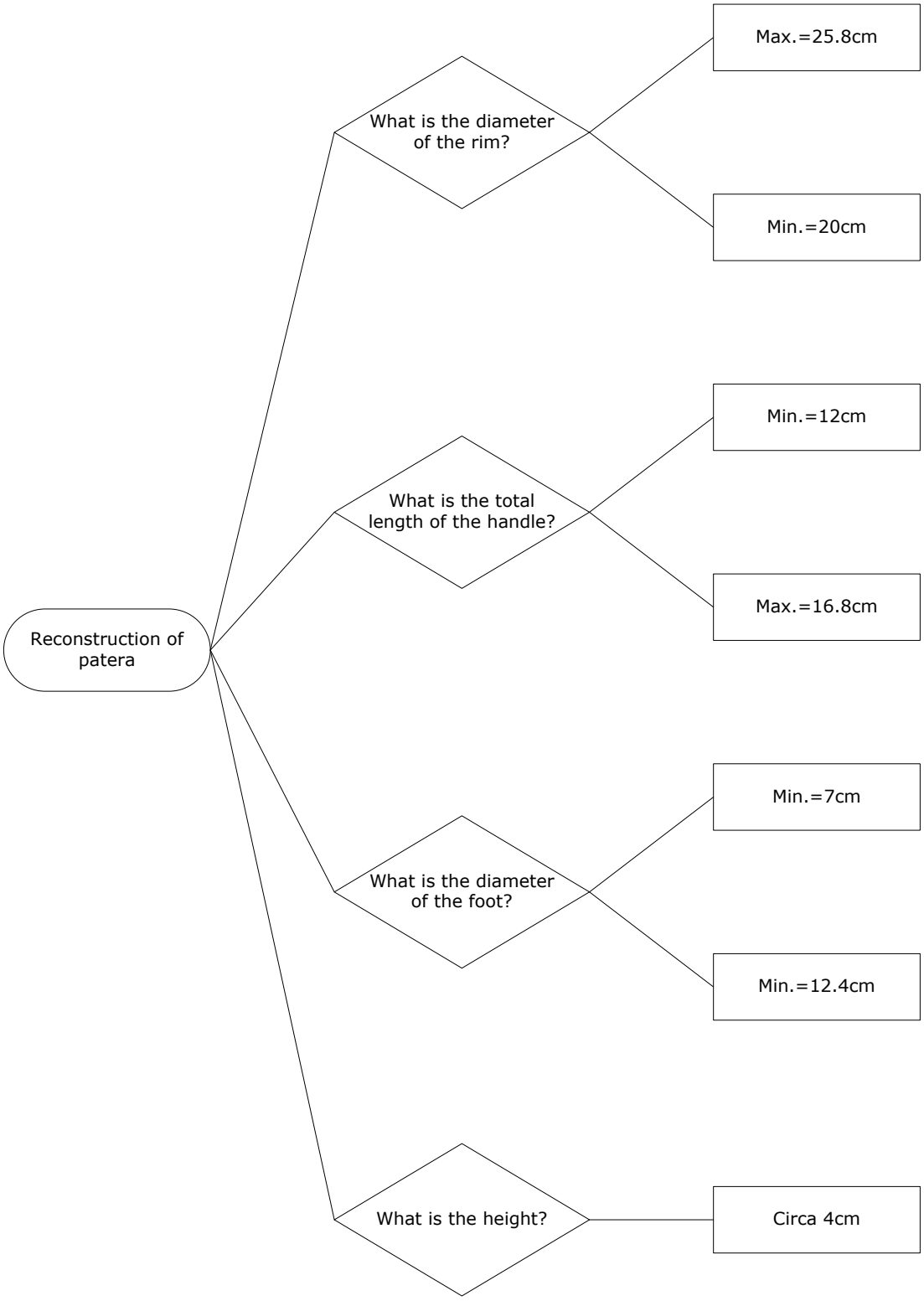
The following list summarises the reconstruction dilemmas for the patera and reveals the complexity of this restoration project:

- What is the total length of the handle?
- What is the height?
- What is the diameter of the foot?
- What is the diameter of the rim?
- Is the foot part of the patera? If yes, which is its correct position?
- Are the mounts parts of the patera? If yes, which are their correct positions?
- Which of the thin bronze sheets, if any, are parts of the patera?

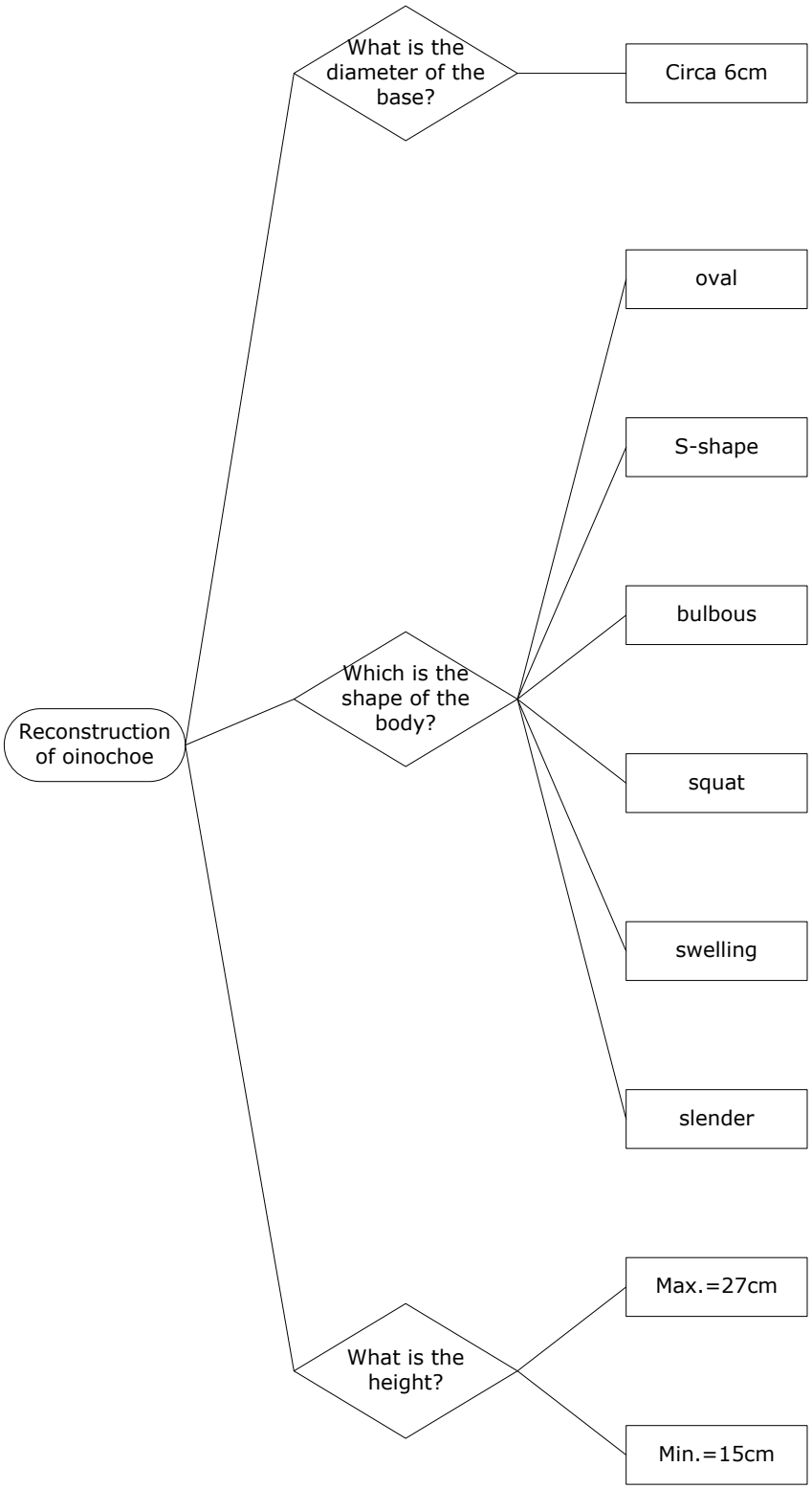
The following list summarises the reconstruction dilemmas for the oinochoe:

- Which is the exact shape-curvature of the missing area of the body?
- Which is the diameter of the base?
- Which is the height?
- Which of the thin bronze sheets, if any, are parts of the oinochoe?

The main reconstruction dilemmas are described in Graphs 48 and 49.



Graph 48: Main reconstruction dilemmas for the patera (Graph author's own).



Graph 49: Main reconstruction dilemmas for the oinochoe (Graph author's own).

6.3.4.4 Virtual reconstruction

The total length of the two handle parts is 12.4 cm (8.7+3.7 cm) while the length of handles of similar type varies from 12 to 16.8 cm. Hence, the length of the missing part is approximately between 1 and 4cm. The diameter of tubes varies from 1.7 to 2.8 cm based on the examples already referred to, while the diameter of the fragment is 2.5cm. The diameter of the surviving fragment of the base is around 8 cm. It is likely that this measurement corresponds to the diameter of the foot, because of the tensions in area of connection between the body and the foot may have caused the fracture. In addition, this value is in accordance with the diameter of the foot in similar examples (from 7 to 12.5 cm.). Considering the curvature at the end of the fragment that attaches to the body and the height, which is less that 4cm based on complete examples, an estimated value of the diameter of the foot can be set. Similarly, the known diameter of the rim from complete vessels (from 20 to 25.8 cm), the maximum height and the curvature of the body can be used so as to set an estimated value for the diameter of the rim. Considering the above the final dimensions of the reconstructed vessel were defined (handle length=14.5cm, diameter rim=19.5cm, height=5.3cm, diameter base=8.5cm) (Table 26)[69].

Table 26: Dimensions for the reconstruction of the patera.

	Known value	Maximum value from examples	Minimum value from examples	Estimated value
Handle length	12.4	16.8	12	14.5
Handle diameter	2.5	2.8	1.7	2.5
Height	-	4	-	5.3
Rim diameter	-	25.8	20	19.5
Foot diameter	-	12.4	7	8,5

A number of renderings were produced, such as non-photorealistic renderings (Figure 399) and renderings of the complete vessel (Figures 400-401).

[69] See Digital Library, folder section6.3, file HMS_UK_COP_PATERA.max

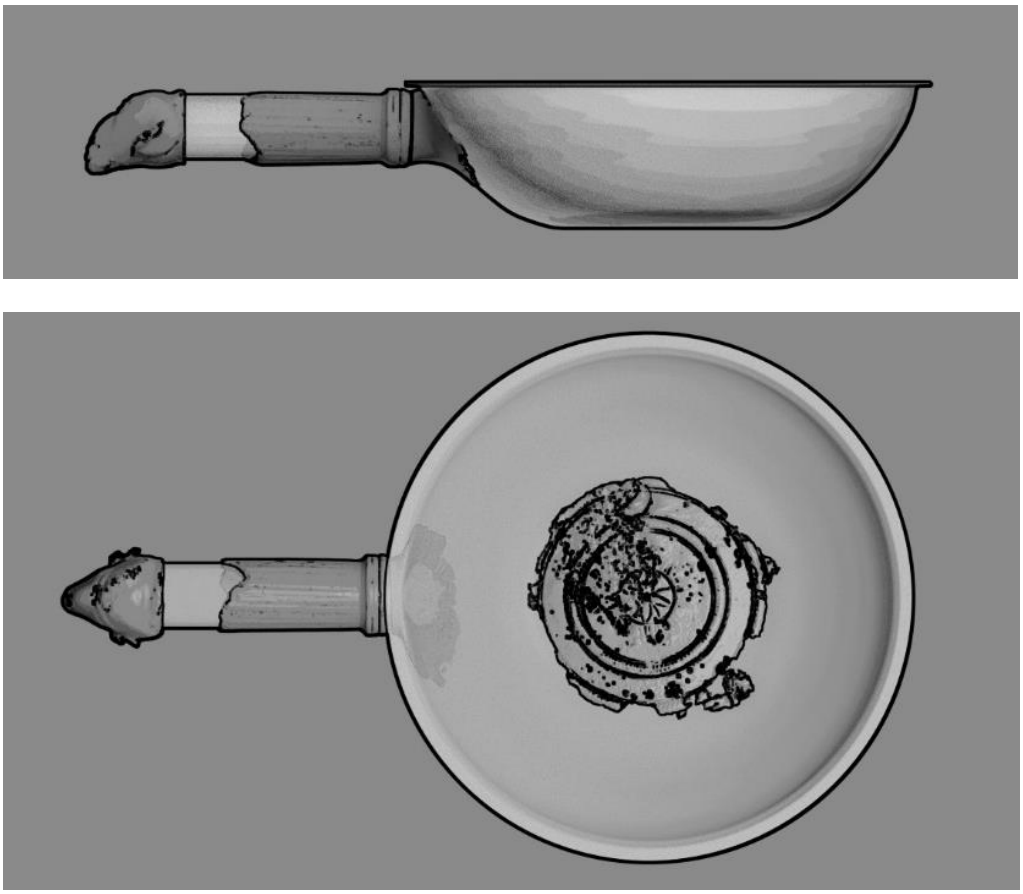


Figure 399: Drawing of the vessel, side and top view, created in 3D Studio max (Image author's own).

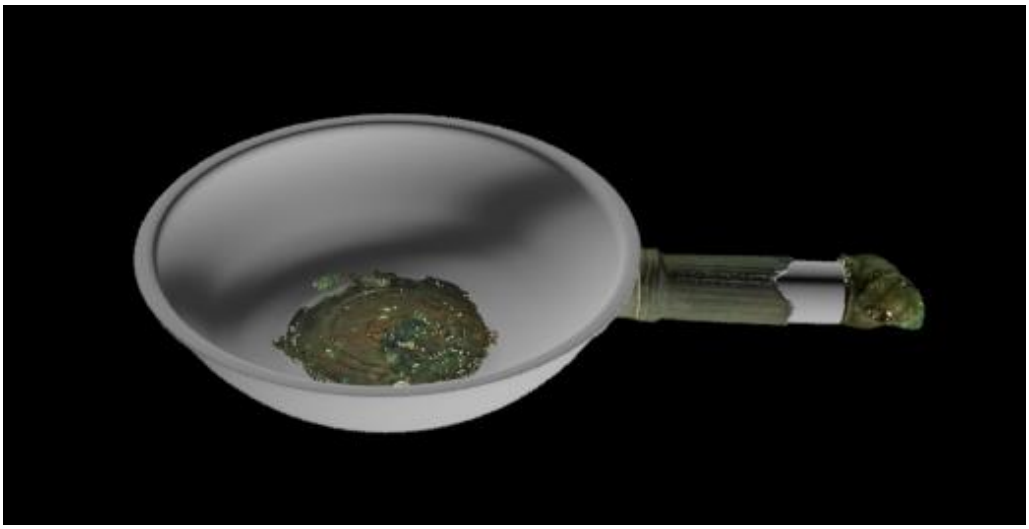


Figure 400: Rendering of the vessel, side view, created in 3D Studio max (Image author's own).

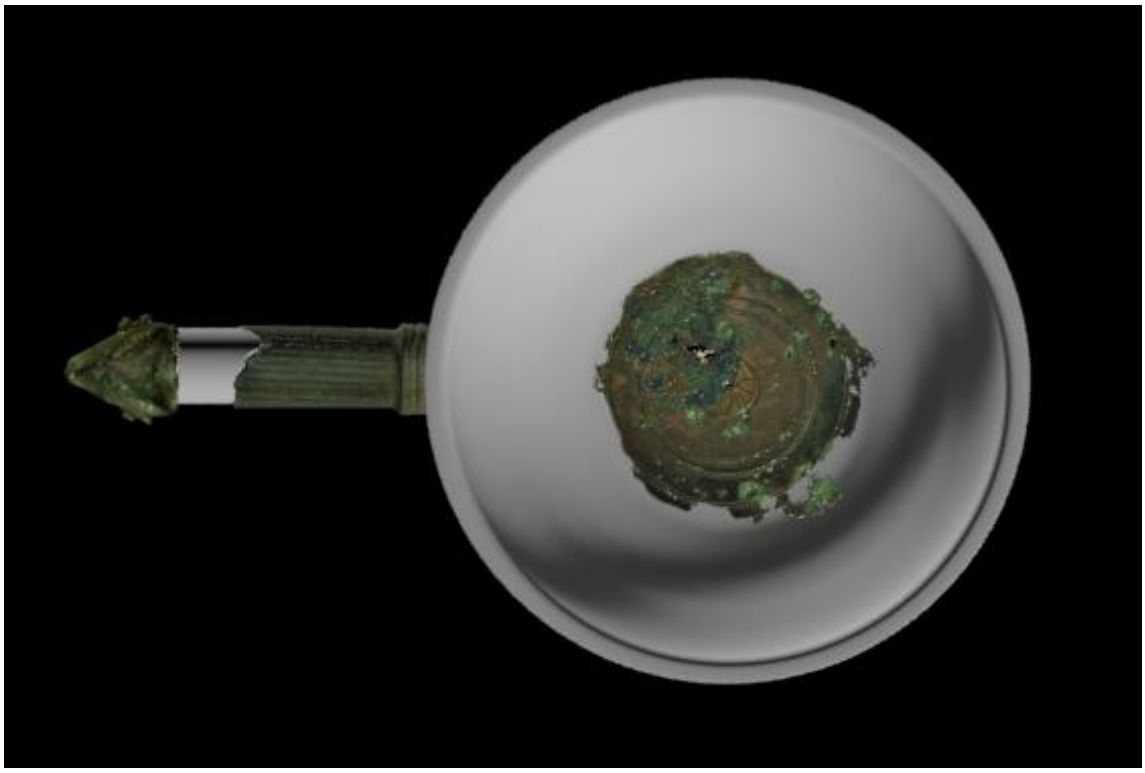


Figure 401: Rendering of the vessel, top view, created in 3D Studio max (Image author's own).

From the shape of the surviving part of the body, the conclusion that the oinochoe has an oval or globular body can be reached. Regarding the handle, its shape leads to the conclusion that it resembles the one depicted in the Figure 310. The maximum diameter as well as the height of the oinochoe's surviving part is around 14 cm, and the handle's length is 13 cm, while the lower part of the oinochoe's body is missing. Considering the above, the missing part of the body extends from the end of the handle height in the area of the shoulder to the base. This area covers almost half or one third of the total height. Its curvature is unknown. The surviving part of the base has a radius of around 2.3 cm with a slight indication of a curved area that may define its edge. Modelling of the missing lower body part is problematic because of the distortions. In order to represent the body of the oinochoe as symmetrical, as it should have been, it is inevitable that original material must be covered. Otherwise the reconstructed part would be modelled in a way that follows the distortions of the original material or slightly smaller as shown in Figure 402.

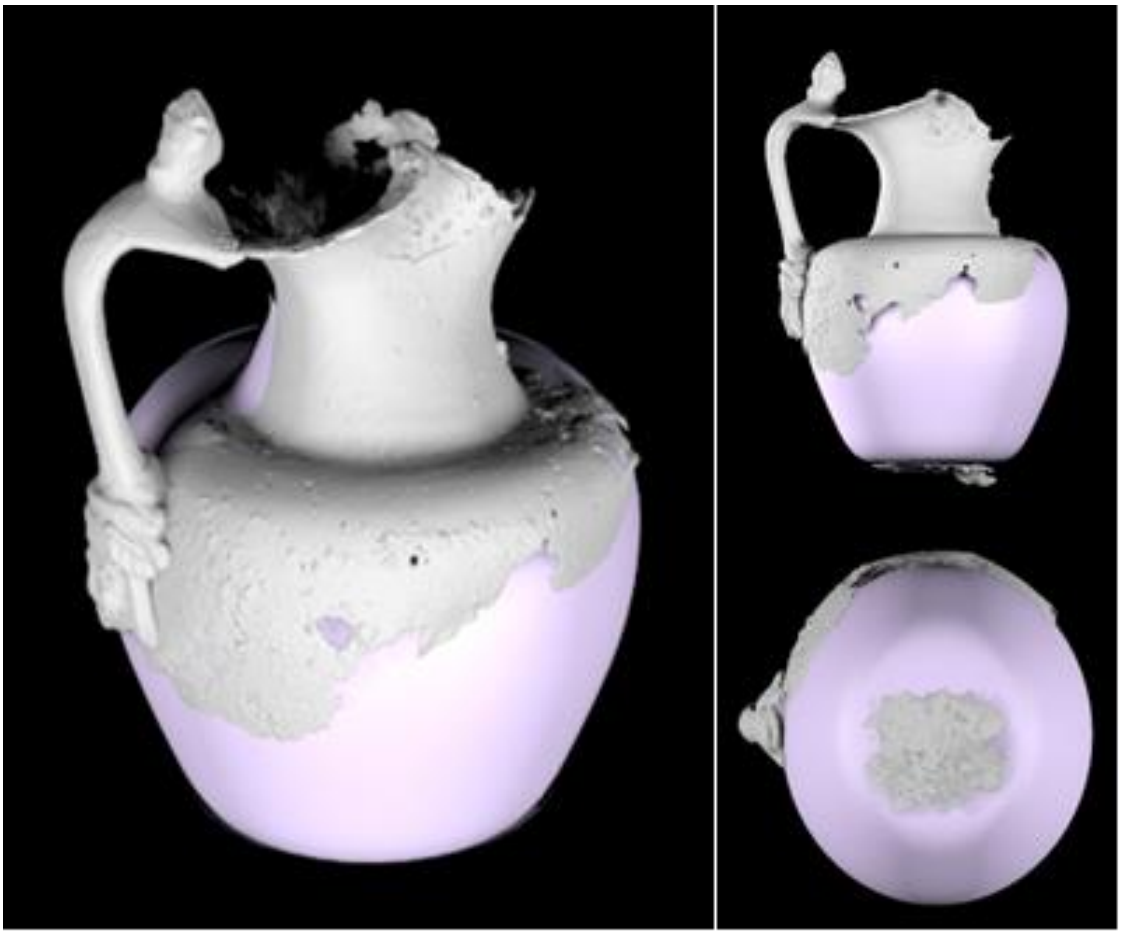


Figure 402: Proposed reconstruction of the oinochoe. Rough estimation of curvature and height based on the surviving evidence (Image author's own).

6.3.4.5 Virtual aesthetic restoration

The virtual aesthetic restoration aims to define the appropriate appearance of the fill. In order to achieve this goal a series of materials was created. Via the comparison of renderings the user can evaluate the success of the aesthetic restoration. In order to transfer the *6 foot 6 inches* rule in a virtual environment, cameras were positioned so as to produce close up and distance renderings as shown in Figure 403. The former focus on the details of the handle and the base, while the latter produce top and perspective views of the whole vessel.

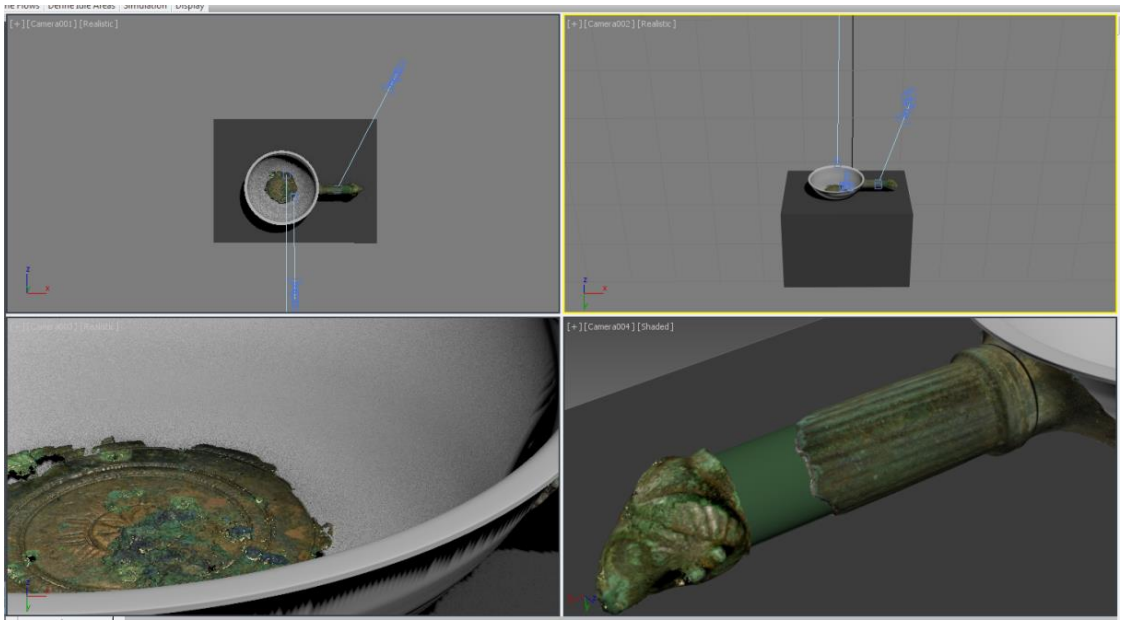


Figure 403: Screenshot from 3d studio max, showing the distance views of the whole vessel (top) and the details (below). Clockwise from top left, view from Camera001, 002, 004 and 003 (Image author's own).

The renderings with a material that resembles the optical properties of Plexiglas (Figure 404), in terms of colour and translucency, was used as an initial point for the experimentations. A restoration like this would succeed in the representation of shape of the vessel and would make it accessible and understandable to the viewer. Nevertheless, its aesthetic quality resembles neither complete examples nor the artefact in its historical form. Similarly, the application of a simple greenish colour (Figure 405) creates an unrealistic appearance.

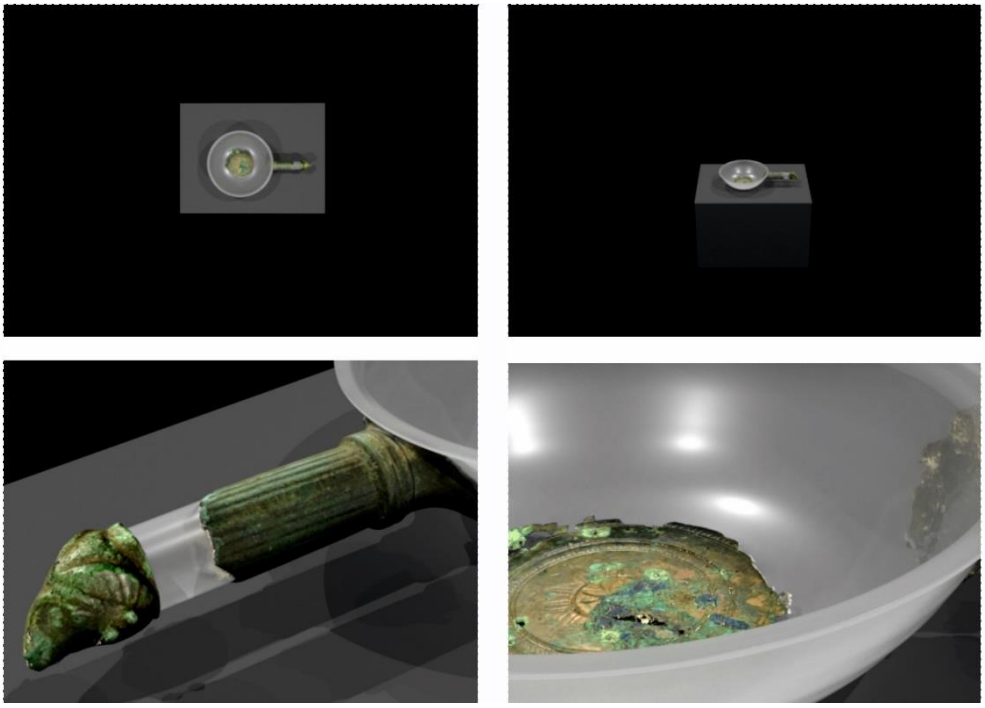


Figure 404: Renderings with a material that resembles the optical properties of the Plexiglas applied to the modelled parts. Distance views (top) and details (below) (Image author's own).

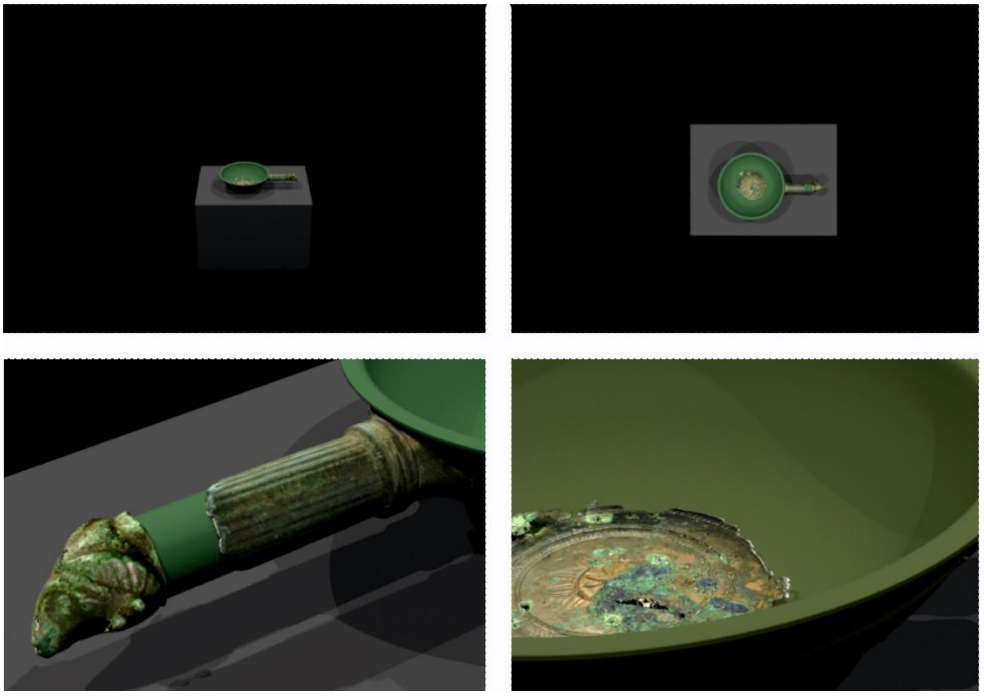


Figure 405: Renderings with a greenish material that resembles the optical properties of matt plastic or painted gypsum applied to the modelled parts. Distance views (top) and details (below) (Image author's own).

In contrast, for the handle the application of a diffuse colour map gives much more realistic results (Figure 406). The viewer can distinguish the modern addition even from the distance renderings. However, this is not possible when a cellular diffuse colour map, which combines brown and greenish hues, was applied (Figure 407). The latter proved to be the most appropriate material, because it is clearly discernible in the close ups, while in the distance renderings it is not distinguishable from the original material. For the missing part of the body of the patera a cellular material was used. As shown in Figure 408 the different tiling of the map has an impact on the appearance of the restored vessel.

Figure 406: Renderings with an image of the handle as diffuse colour map. Distance views (top) and detail (below) (Image author's own).

Figure 407: Renderings with a cellular diffuse colour map applied to the modelled parts. Distance views (top) and detail (below) (Image author's own).

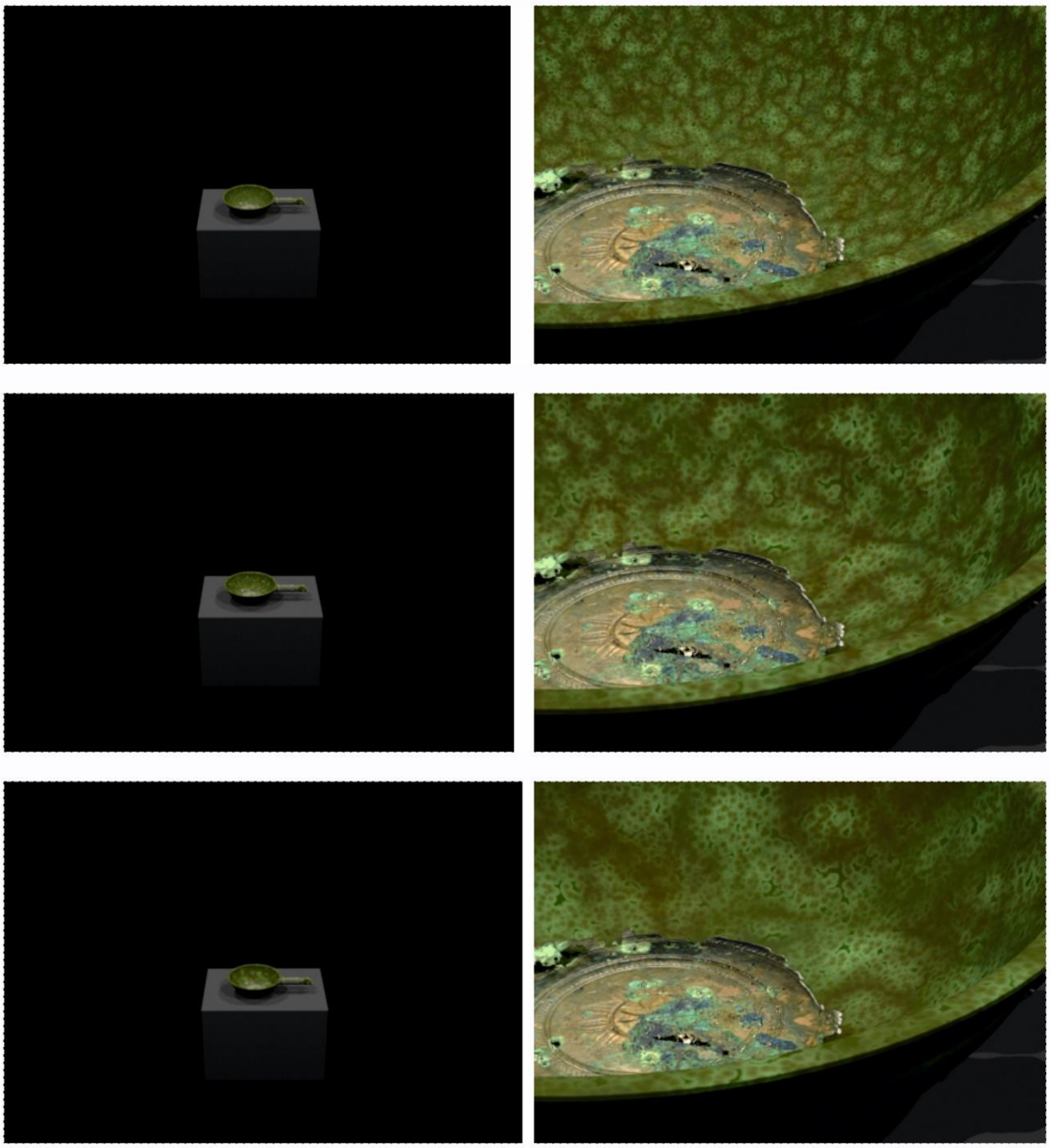


Figure 408: Renderings with a cellular diffuse colour map with different tiling applied to the modelled parts. Distance views (left) and details (right) (Image author's own).

6.3.4.6 3d printing design

The modelled detachable fills can be 3d printed and attached to the original parts (see section 2.3.2.5 for an overview on 3d printing). Particular attention should be devoted to the geometric accuracy of the 3d printed parts. Deformations occurred during and/or after the printing, loss of details during post processing and low resolution and or high speed 3d printing would result in mismatch or bad cohesion between the original and the fabricated part. In such case the only way to use the 3d print would be its manual reshaping, if this is possible, considering its shape, material and size. Hence, high resolution and low speed 3d printing with materials that provide better representation of detail and careful 3d modelling following the guidelines are recommended.

Another crucial issue is the interaction between the 3d print and archaeological object. Similarly to conventional restoration methodology (see section 2.2.2.3), the materials used as fillers should not encourage further degradation and contamination. Fragmented, incomplete and restored artefacts are not suitable for handling session, so the requirements of the material are limited to its optical and chemical and mechanical properties. The desired colour can be achieved, either by using the appropriate colour finishing or by attaching a printed image of the desired colour on the surface of the 3d print. The mechanical properties (strength, density etc.) of the 3d printing material are known and their performance can be calculated with finite element analysis[70] and other more specialised simulation techniques, in order to avoid forces that may cause damage to the object. Considering that plastic is lighter than metal, it is expected to meet the requirements of conservation for the bronze vessels.

Due to the lack of research on the interaction between 3d printing and archaeological materials, the only available solution is to propose the closest approximate to conservation materials used in conservation. Considering the current state of research plastics are preferred because they are the more

[70] Finite element analysis is a computational method for simulation of real-world forces. Specialised software is being used for such simulations (ansys, autodesk) and applications in archaeology and artefacts' studies have been presented (Foecke *et al.*, 2010; Levy and Dawson, 2009; Hein and Kilikoglou, 2015).

advanced materials in terms of 3d printing and they have more controllable properties. Nevertheless, it is difficult to find a material that fulfils all the requirements. For example, the use of an acrylic based plastic material, recommended for the fabrication of detailed products[71] is not strong enough. Other materials that present better mechanical properties are not suitable for detailed models[72]. A potential solution to this problem is the use of multi-materials[73], because they can fulfil the requirements in terms of optical and mechanical properties. For example, the 3d print part that is actually in contact with the original can be printed in a material that presents best chemical properties, in order to avoid degradation and contamination. The other part can be printed in a material that best matches the optical properties of the original. Another option is the use of multi-materials for the positioning of the 3d printed part instead of using adhesives. In case of the modelled missing part of the handle, the parts that should be inserted can be 3d printed in elastic plastic material so as to be attached to the original parts. The visible part of the handle can be 3d printed either in metal or in plastic (Figure 409-410). The proposed methodology proposed is represented in the Open Provenance Graph 50.

Figure 409: Rendering of the restored handle created in 3D Studio max (Image author's own).

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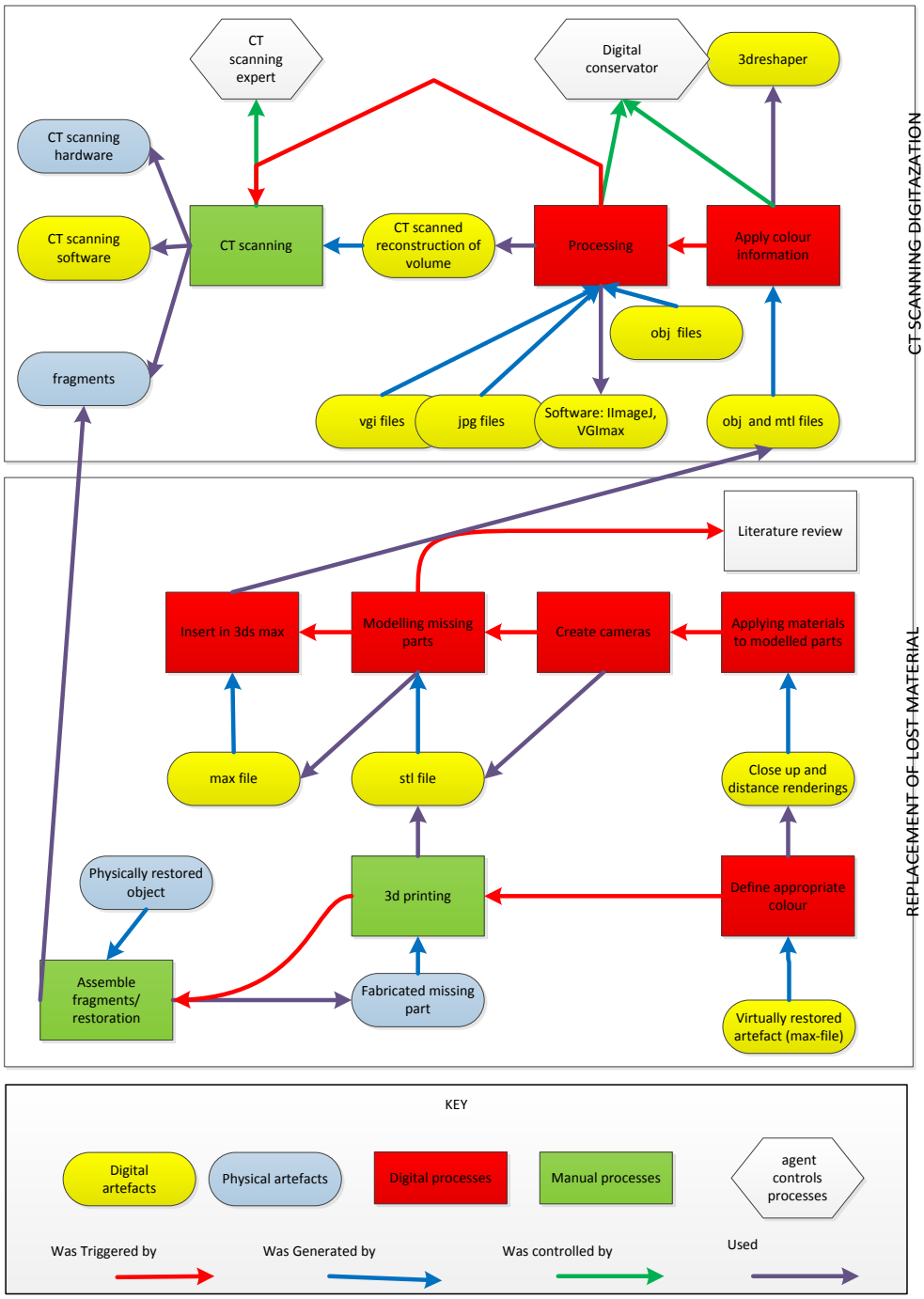
[71] For example the detail plastic (http://www.shapeways.com/materials/detailed-plastic) and frosted detail plastic (http://www.shapeways.com/materials/frosted-detail-plastic) both provided by shapeways.
[72] For example the strong plastic material provided by shapeways http://www.shapeways.com/materials/strong-and-flexible-plastic
[73] For more details of multi-materials research see Vidimče et al. (2013).

Figure 410: Renderings from different views of the modelled missing part created in 3D Studio max (Image author's own).



Graph 50: Open Provenance Graph for the methodology proposed for replacement of lost material (Graph author's own).

6.4 Re- and de- restoration

6.4.1 Scope

For the third case study the main goal is to use the techniques discussed throughout the thesis in an attempt to define an *ideal* state, balance the conservation objectives and lead to a better treatment proposal, taking in to account methodologies derived from conventional conservation practice.

6.4.2 Selection of study material

A highly corroded iron pocket sundial was used as a case study (Figure 411) in an attempt to explore the possibilities of virtual reconstruction and physical replication in case of de- and re- restoration projects. The iron pocket circular sundial was selected due to its complexity and advanced level of difficulty in terms of conservation decision making, considering the poor preservation state, the old conservation operations as well as the interest in its use. It is highly corroded and extremely fragile. It survives in two parts, in a mass of compacted chalk material. The physical structure of a sundial which casts the shadow (gnomon), which usually lies on the dial plate or face, is lost. Similarly, the hour line, numerals and furniture are hardly discernible.

Figure 411: Iron pocket sundial fragments (Image author's own).

6.4.3 Methodology

For the re- and de- restoration case study the conservation treatment methodology (characterization grid, values analysis, timeline) proposed by Appelbaum (2009) will be enriched with the digital components discussed in the previous sections, as well as the digital capture techniques presented in Chapter 5 (PG and RTI).

For recording and documentation of the sundial fragments and revealing the material evidence microscopy, multispectral Imaging, PG and RTI were employed. All the relevant documents from the institutional archive were studied, including the excavation data and notes and the conservation reports, in order to understand the object biography. Archives and literature research was conducted in an attempt to select data regarding sundials, including manufacturing technology, materials and use and typology. Based on the information selected and analysed the *'ideal'* state of the artefact will be defined, in an attempt to reach a compromise between conservation objectives. Finally, the appropriate treatment proposal will be presented.

6.4.4 Results and discussion

6.4.4.1 Archives and literature research

According to the museum documentation and the entry about the sundial in the archaeology object database (find no A.2000.134.300), the object is dated around the 15th century AC. It was unearthed in the excavation of the Woollen Hall, Castle Way (SOU 393), a 12th century family house with a 13th century vaulted cellar below. The intensive occupation from the 900's until 1940 ended after the house was destroyed by a massive fire. Excavation revealed the wealth of the owners of the house, possibly rich merchants, who possessed exotic imported objects, such as Italian and French pottery and glass vessels and fine metal work. Through documentary evidence, the owner of the house, a wealthy merchant called Agnes Overy, was identified. The object was transferred to Salisbury conservation centre and underwent preliminary conservation treatment, including removing the wet soil, cleaning, joining with HMG cellulose nitrate and consolidation with Paraloid B72. Mechanical damage caused during cleaning was also consolidated. Margret Brooks noted the

fragility of the object, which was reduced to a brittle, bubbly corrosion at the back and grey residual iron on the front. In the conservation report the lamination of the surface was stated clearly: '*...the object has split into two upper and lower slices and they are not object or cover or lid*' (Southampton City Council, Arts and Leisure Archive).

The sundial is one of the oldest instruments for telling the date and measuring time from the position of the Sun. During the 15th and the 16th century, Germany, and in particular Nuremberg and Augsburg, were the main production centres for portable sundials (Freitag, 2011). Also, this instrument was very popular in medieval and early modern Europe, and remained an essential item for many people until the 19th century. During the Middle Ages only a limited number of people could afford to own a sundial, while the vast majority calculated time by listening to the bells of the local church, or by the position of the sun in relation to local landmarks (Eagleton, 2005). Waugh (1973) refers to the need for portable sundials for travellers who want to keep track of time into the early seventeenth century, when pocket watches became more reliable and less expensive. Although sundials were luxury objects for that time, various types of inexpensive portable dials were used by common people.

Portable sundials existed in various types, including cylinder, tablet, cubic, cross, equatorial and ring as well as nocturnal sundials. These transportable sundials include some means of orienting the dial, and they are often either universal or capable of being read at a number of fixed latitudes. Nocturnal sundials were widely used by sailors. They consist of three parts. The first one is a circular disc divided around its edge in 12 divisions, representing the months. The second is a slightly smaller disc with 24 divisions, one for each hour of the day. The third part is a cursor that passes though the centre of the pivot plate (Figure 412). The equatorial sundial has a similar division in its face so as to represent the hours of the day, with 15 angles for each hour and a gnomon set perpendicular to the dial plate in the centre of the dial. To use it in the winter the dial must have the same numbering on the back side of the

plate (Figure 413)[74]. Pocket equatorial dials were popular in Ausberg, Germany. The dial furniture, other than the hours line and the meridian, are additional lines and features which are not absolutely necessary for telling the time (Waugh, 1973).

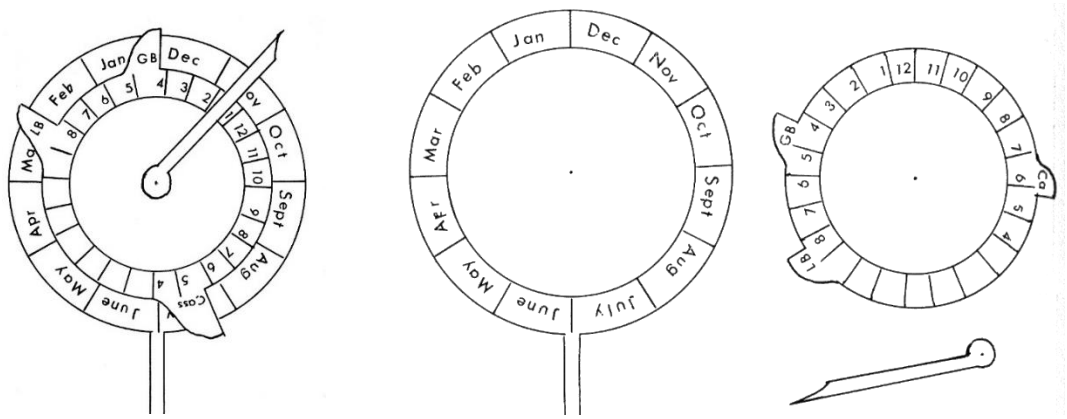


Figure 412: The nocturnal sundial (left) and its assembly (right) (Waugh, 1973).

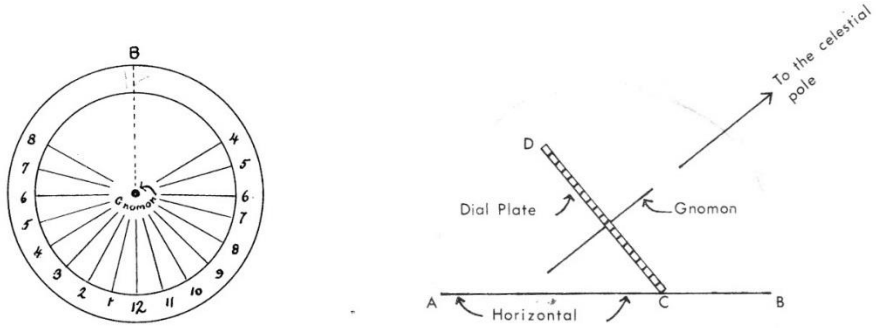


Figure 413: Equatorial dial, top (left) and side view (right) (Waugh, 1973).

6.4.4.2 Material evidence

Microscopic examination of the sundial fragments revealed details of the decoration and degradation phenomena. The stippling was evident in well preserved areas, although an indication can be seen in the case of severely damaged letters (Figures 414-415). The surface is covered by deposits, encrustations, materials from the excavation environment and corrosion

[74] The website of The British Sundial Society is a useful resource for more details on sundials (http://sundialsoc.org.uk/)

products (Figures 416-417). Severe physical damage, in the form of cracks and losses, were also evident. A difference in reflectivity due to the presence of films of conservation materials and glues in the areas of the cracks were documented (Figures 418-419).

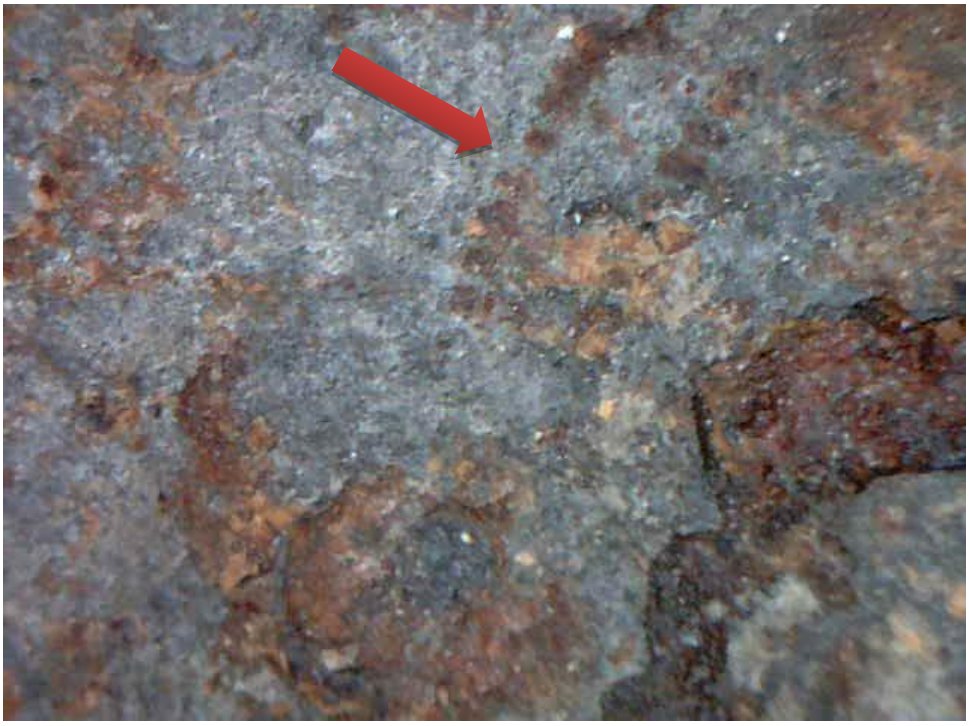


Figure 414: Microscopic details of numerals, clear visualization of the stippling in a relatively well preserved area (Image author's own).

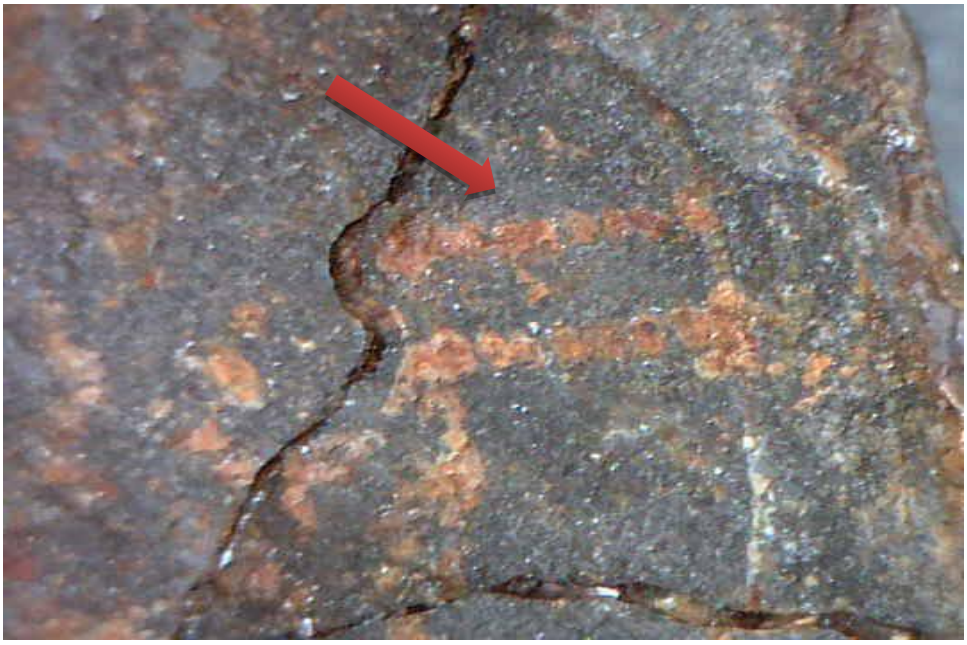


Figure 415: Microscopic details of numerals, indication of stippling in a damaged area (Image author's own).

Figure 416: Accumulation of deposits, dirt and salts in the interface between the iron and the chalk (Image author's own).

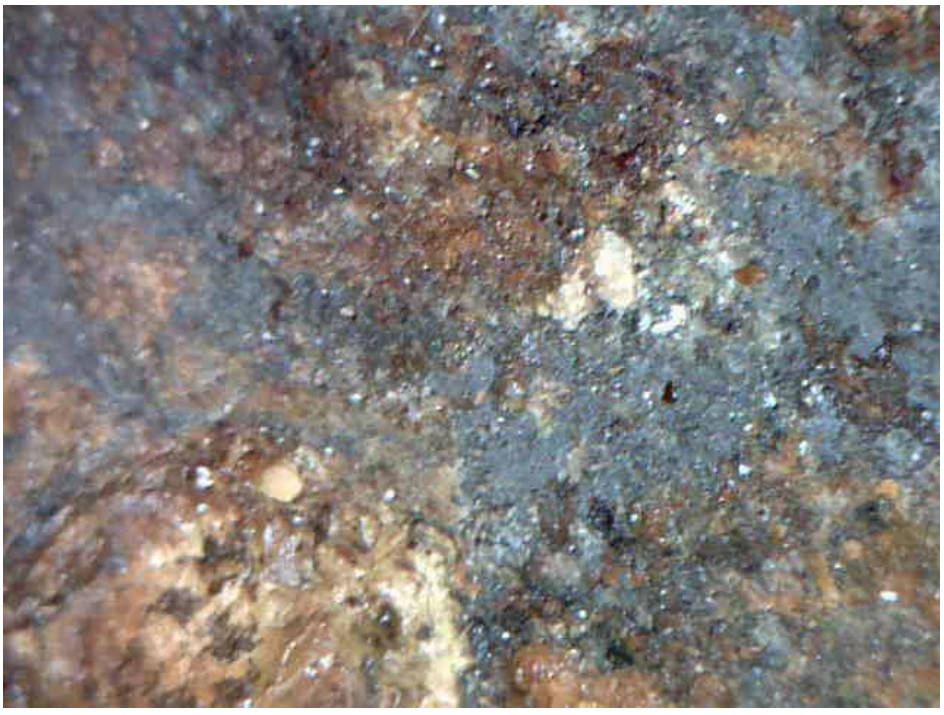


Figure 417: Deposits, encrustation and corrosion products on the surface, microphotograph (Image author's own).

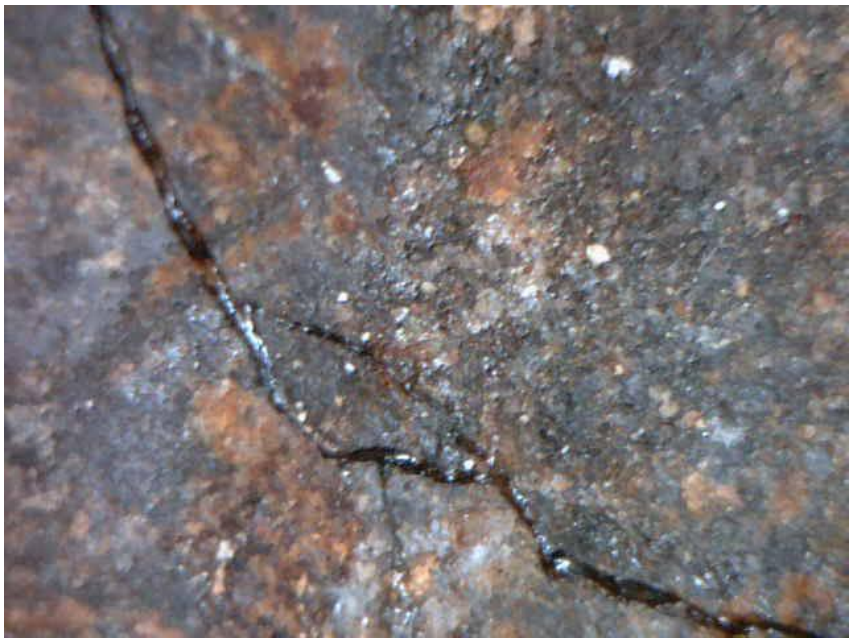


Figure 418: Cracks, microphotograph (Image author's own).

Figure 419: Area of loss, microphotograph (Image author's own).

In greyscale images the hole in the centre of the sundial is hardy recognised, while in the infrared images it is clearly differentiated from the metal material (red arrows-Figures 420-421). One of the most interesting features was the enhanced legibility of certain numerals in the infrared spectral area (yellow arrows). But this phenomenon is not uniform, as other details and numerals appear less distinctive in infrared images (green arrows). This demonstrates

the complex corrosion pattern that has been formed, with various depositions, corrosion products, and crusts of different chemical compositions on the surface of the sundial. Certain corrosion products appear opaque in IR images. The digitised old x-radiographs emphasize the absence of other materials (e.g. brass) and the corrosion of the sundial (Figure 422).

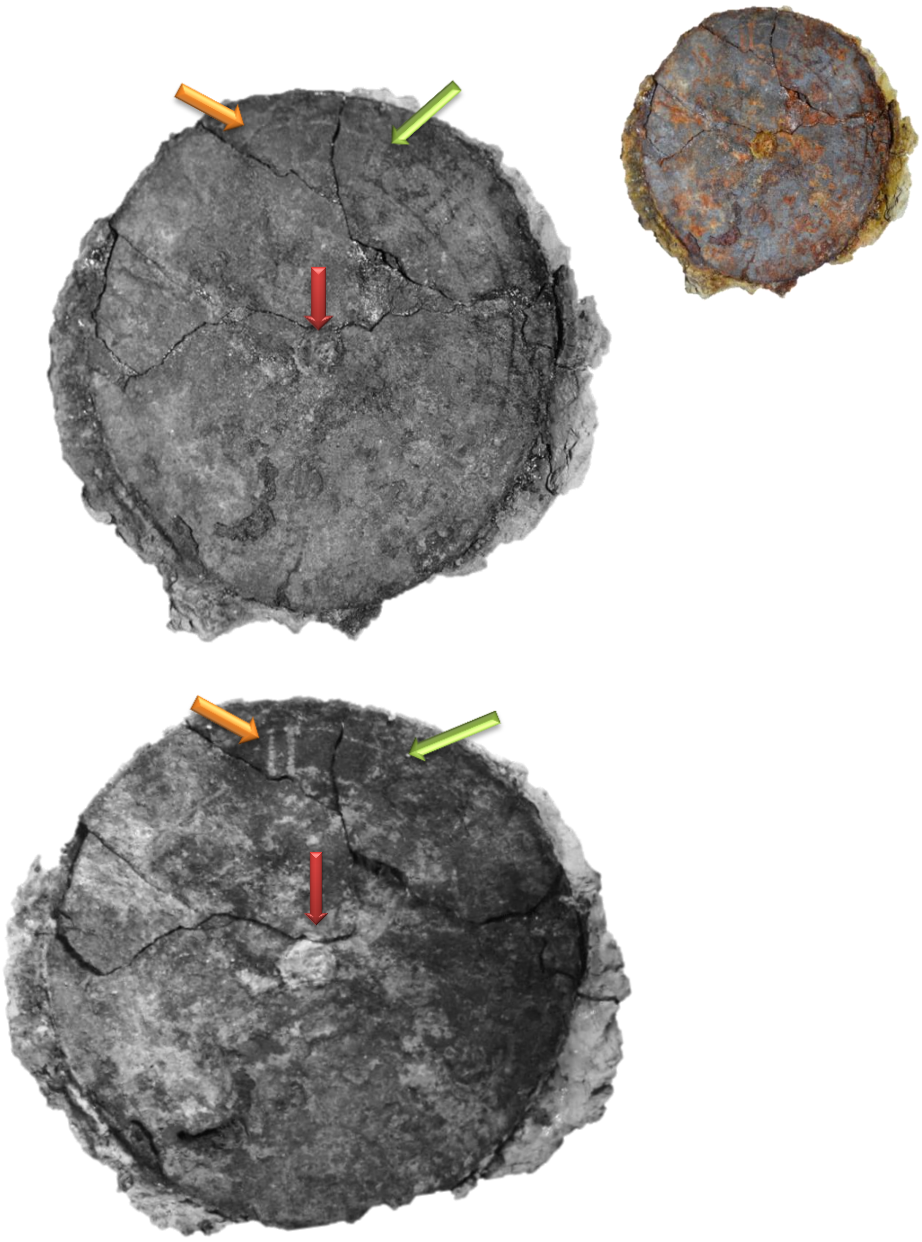


Figure 420: Sundial fragment, digital, greyscale image (top) and IR image (below) (Image author's own).

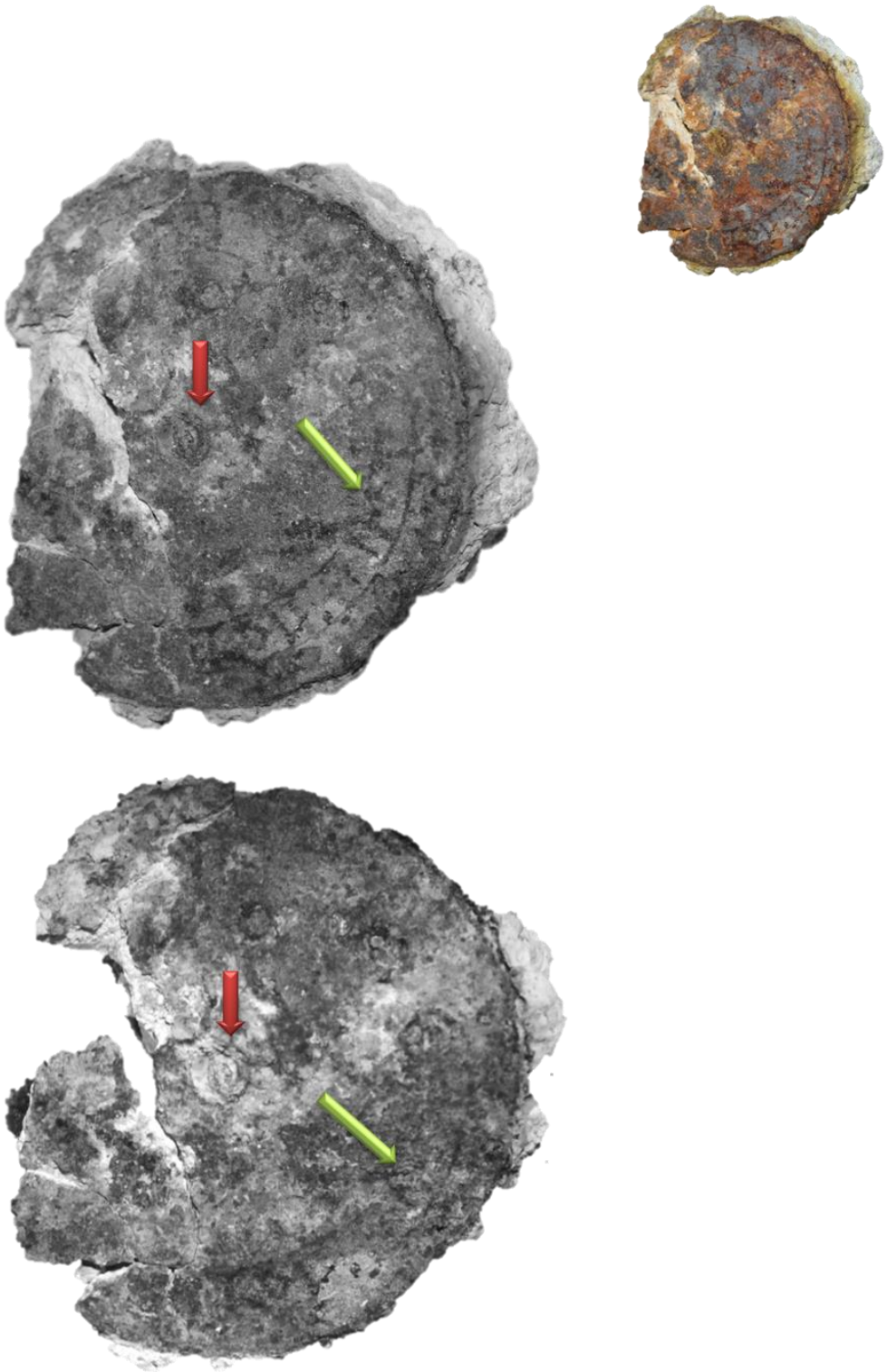


Figure 421: Sundial fragment, digital, greyscale image (top) and IR image (below) (Image author's own).

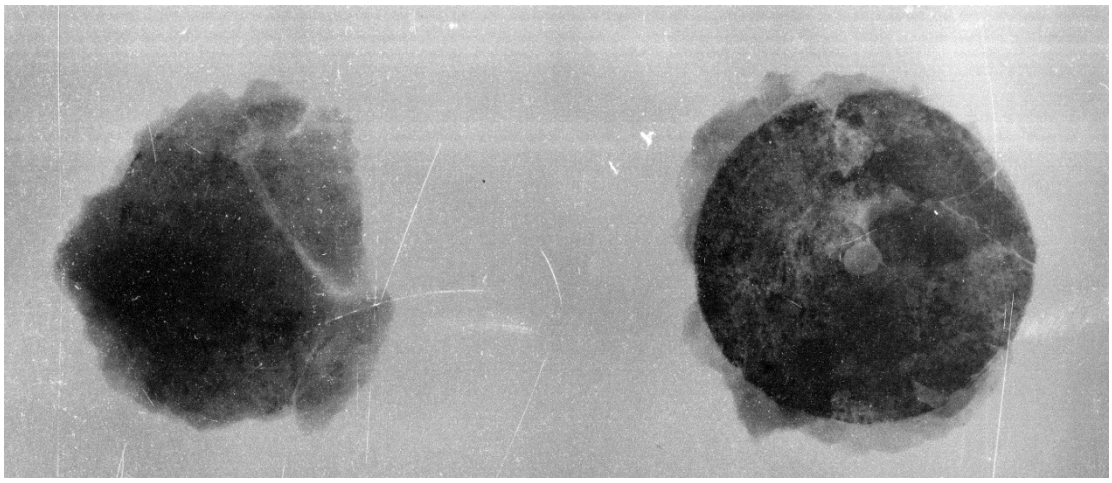


Figure 422: Digitised radiographs. Image for the Archive of the Southampton City Council, Arts & Heritage.

RTI can support documentation and examination as demonstrated in chapter 5. RTI has not yet been applied to sundials, with the exception of a portable bronze sundial from the collection of the British Museum (Bevan *et al.*, 2013), although there is no doubt that the technique can significantly enhance the study of this object type. In this context, because of the complexity and the fragmentary nature of the sundial's face, RTI visualization aimed not only to enhance the legibility of the inscriptions, but also to determine the condition of the object. RTI visualizations assist in documentation and condition recording, and enhance our understanding of its conservation state non-destructively, thus avoiding any form of interaction with the material or handling. An attempt was made to distinguish the hour line and the numerals as well as the furniture on the sundials plate or face. These features, referred to as furniture (declination lines, compass rose, mottoes, date, maker's name and latitude) are crucial for the understanding of the object and its use. However, they are hardly recognisable because of the poor state of preservation (Figures 423-425). The month's line was the only furniture feature revealed in both fragments (Figures 426-427), while the degradation, cracks, deposits, corrosion products and losses were documented[75].

[75] See Digital Library, folder section6.4, files SCC_UK_IROa_SUN_MA-H.rti and SCC_UK_IRObSUN_MA-H.rti

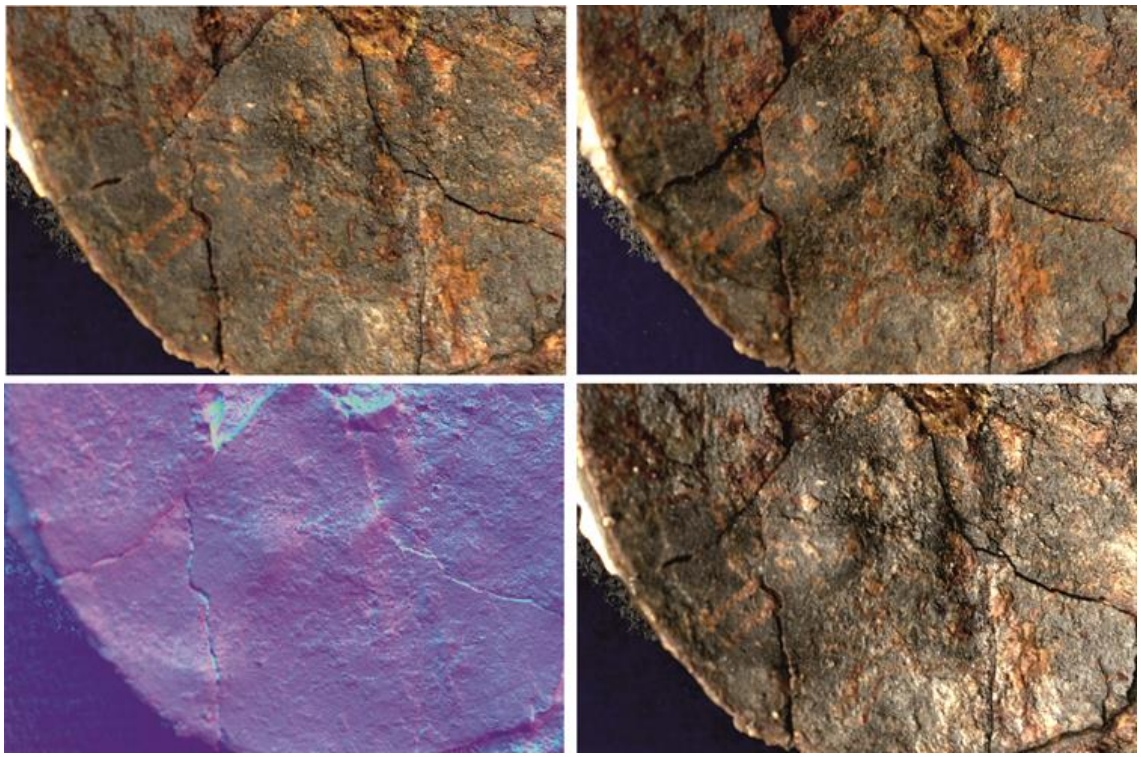


Figure 423: The sundial, detail, clock wise from top left, digital image, RTI visualization in default and specular enhancement rendering mode and normal map. RTI provide enhanced visualization of the surface topography, including the sundial furniture and degradation features (Image author's own).

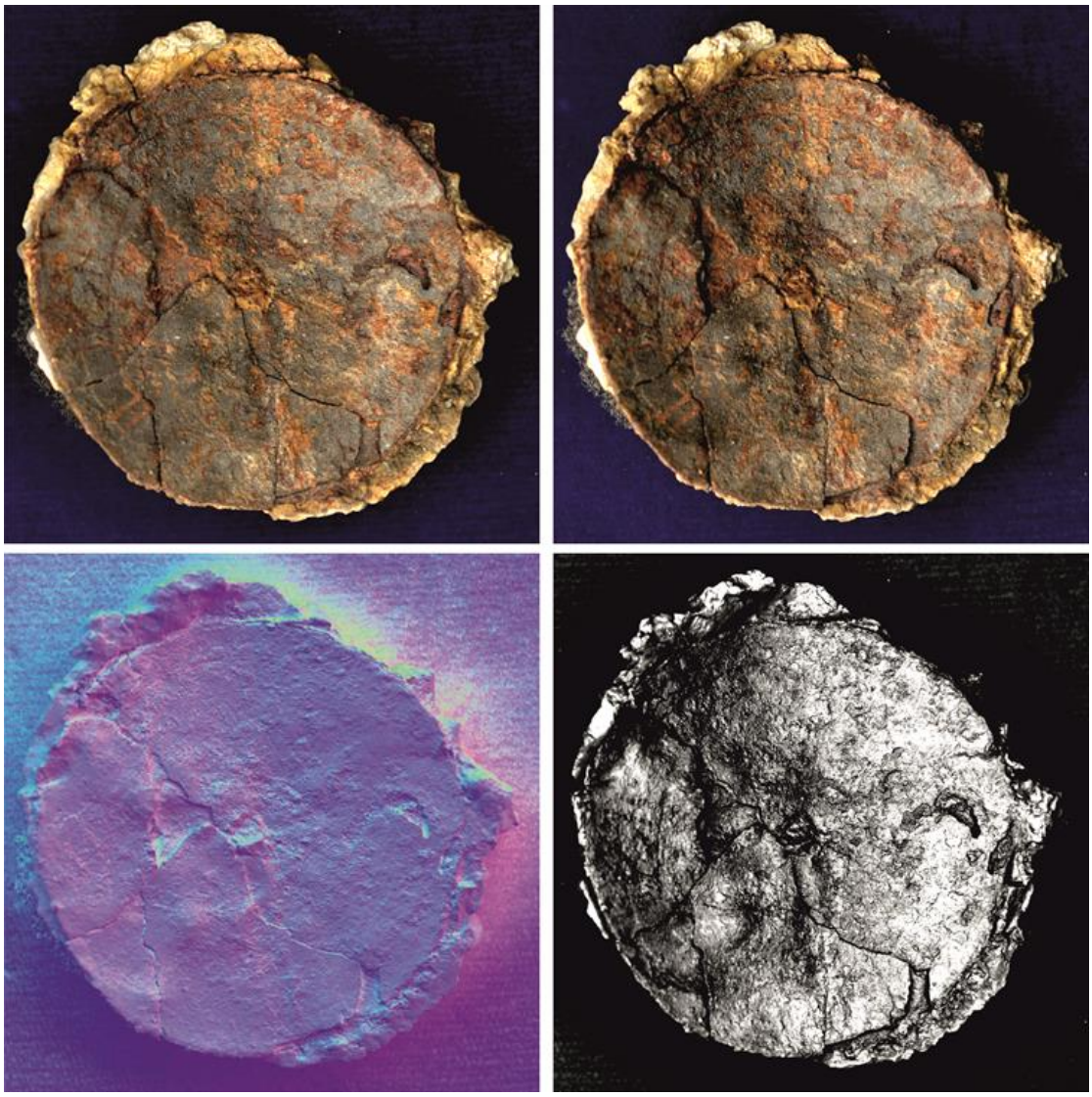


Figure 424: The sundial, clock wise from top left, digital image, RTI visualization in default and specular enhancement rendering mode and normal map. RTI Visualizations emphasizing damage, cracks and encrustations (Image author's own).

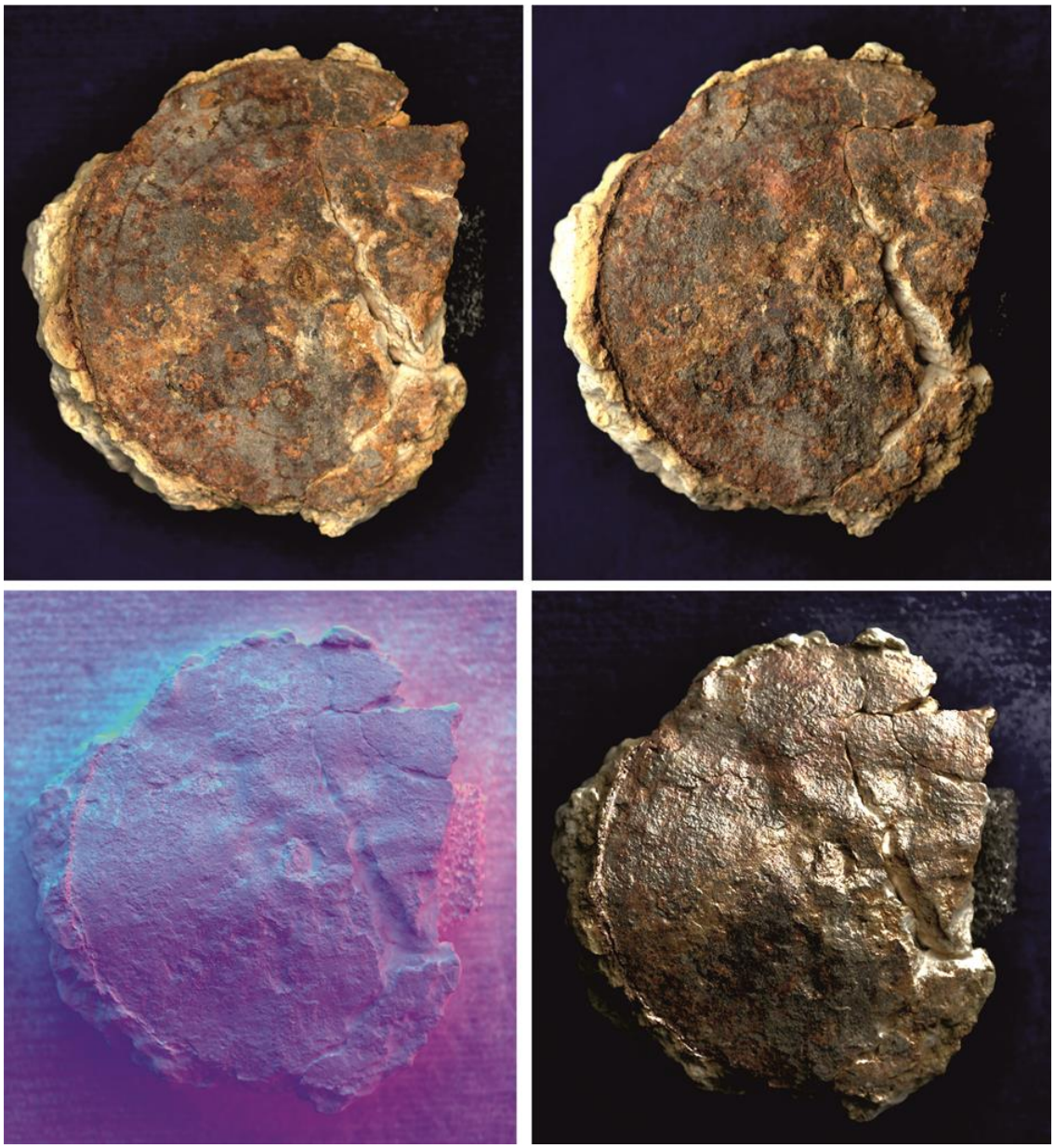


Figure 425: The sundial, clock wise from top left, digital image, RTI visualization in default and specular enhancement rendering mode and normal map (Image author's own).

Figure 426: The sundial, RTI visualization with hour's line revealed (Image author's own).

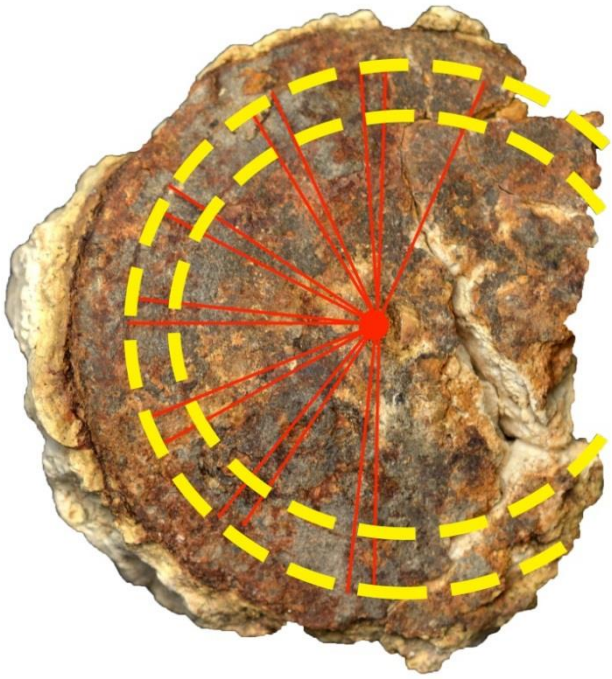


Figure 427: The sundial, RTI visualization with hour's line revealed (Image author's own).

In addition, the 3d model created using PG gave us a better understanding about the shape, emphasizing the curvature of the fragments and enabling dimensional analysis. It also offered the opportunity to test, in a virtual environment, the results of the conservation assessment contacted in 1989 by the Conservation Centre in Salisbury. The two fragments were positioned as indicated by the conservation report, leading to two different scenarios. In the first scenario the small fragments were placed on the top of the larger one while in the second one, the small fragments were positioned upside down (Figure 428). As show in the non-photorealistic renderings the first scenario is highly unlikely compared to the second one, because of the similar curvature of the fragments if positioned in this way.

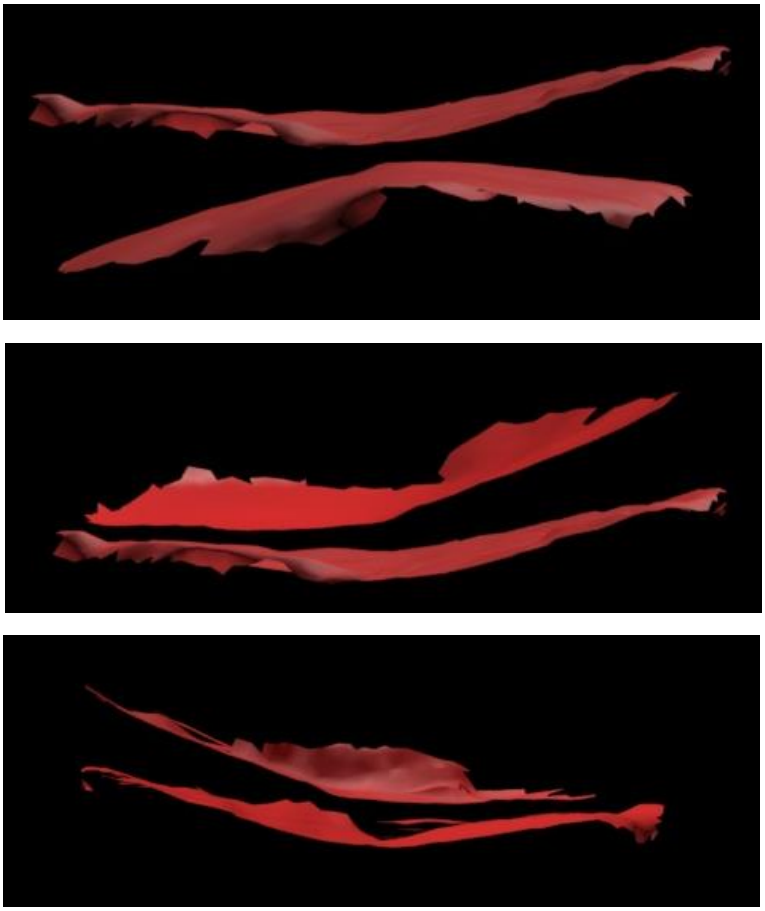


Figure 428: The two fragments, non-photorealistic rendering. A) Highly unlikely scenario of positioning the small fragment on top of the larger one. B and C) Most likely scenario of positioning the small fragment upside down, on top of the larger one (Images author's own).

Although the original reports present the object as having a concave shape, due to the distortion of the fragments it is impossible to reach safe conclusions regarding the original shape. According to the initial interpretation, the fragments were parts of an equatorial sundial (Figure 429). However, there is no reliable evidence that the sundial was of this particular type. This hypothesis is based on the assumption that the numbers 0-8 and 4-12 are engraved on the face of the sundial. Nevertheless, the visible lines do not correspond to Latin numerals, but they are part of the furniture, used to divide the ring into 12 divisions. Based on the material evidence the fragments are probably parts of a nocturnal sundial assembly.

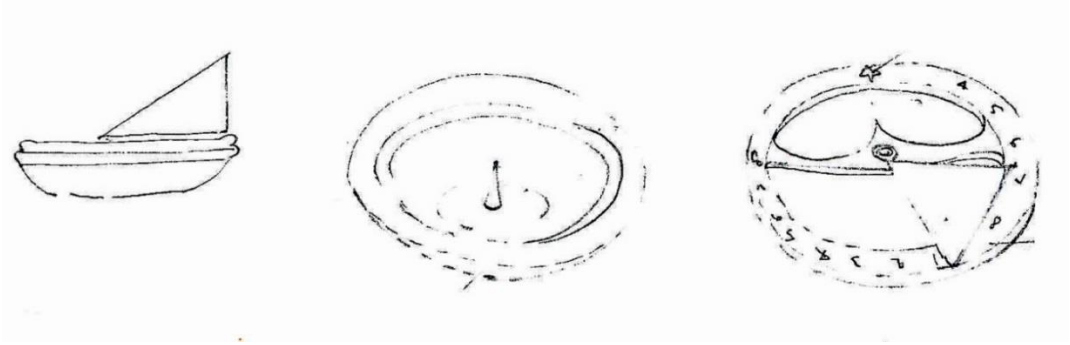


Figure 429: First interpretation of the sundial, sketches. Image for the Archive of the Southampton City Council, Arts & Heritage.

6.4.4.3 Values analyses

Values analyses can help us define the goal of treatment. The state of preservation minimises the art and aesthetic value of the sundial. The highly corroded matter covers any sign that can be useful for the aesthetic appreciation of the object. Although the presence of sundials with elaborated furniture, which are considered as pieces of art, is confirmed by museum collections, such as those of the National Maritime Museum in Greenwich, it is highly unlikely for conservation to manage to reveal the aesthetic quality of the object. Moreover, iron has rarely been the choice of manufacturers of artistic sundials, when other materials, such as iron, copper brass, bone and ivory were preferred. Similarly, the use and educational value of the sundial is limited in its present condition. It is difficult for the museum visitors to understand the object, or for experts to study the object, at its current state. The *rarity* value is relatively high because of the limited number of iron

sundials unearthed in Southampton, as demonstrated by a search in the Southampton archaeology objects database and the Portable Antiquities Scheme database. The rarity of medieval portable instruments has been discussed in the literature (Davis, 2012). Consequently, the object is of particular importance from a *historical* point of view. Its *research* value is of particular importance, as it can potentially provide data so as to better understand the time keeping systems used. The values analysis is summarised in Table 27.

Table 27: Values analysis.

Values		Key
Art value	*7*	***1. Maximum***
Aesthetic value	*7*	***2. High***
Historical	*3*	***3. Possible high***
Use	*7*	***4. Medium***
Research	*1*	***5. Possible low***
Educational	*7*	***6. Low***
Rarity	*2*	*7.* ***Minimum***

6.4.4.4 Treatment proposal

In its present state the physical restoration of the sundial would require removing the chalk, and cleaning and joining the two pieces. Further restoration is required in order for the two fragments to be joined physically, because of the significant loss of material in the edges, as a result of the extensive corrosion and the cracking of the iron. Questions arise as to whether such operations are feasible because of the extremely poor state of preservation of the material. In addition, the final result of such conservation treatment, the state of the object, is under question. It is absolutely necessary to proceed to the replacement of the lost material in order to physically join the two pieces. Based on the findings of the 3d modelling, the highly corroded iron material and the relatively small dimensions of the surviving fragments, physical restoration is not recommended. In order to overcome the uncertainty of such remedial operations, virtual restoration can be performed.

The alternative digital restoration guarantees enhanced accessibility to the object and the protection of its material and aesthetic integrity. Virtual reconstruction[76] overcomes the limitations of physical restoration and offers the opportunity to execute any operation virtually. Moreover, virtual restoration offers the option to erase the damage and represent the object, following the different scenarios (Figures 430-431).

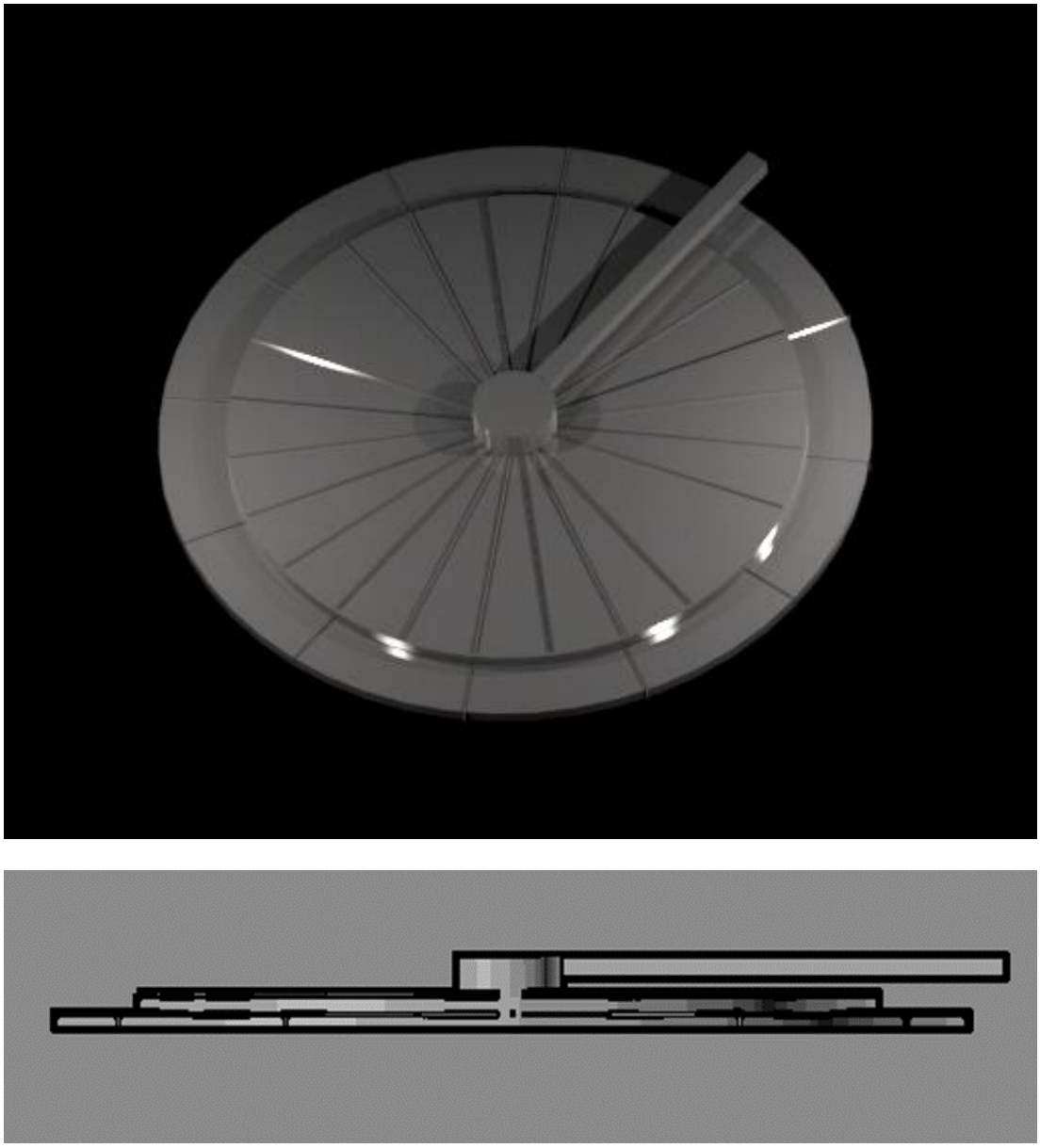


Figure 430: Renderings of the sundial. Nocturnal sundial (Image author's own).

[76] See Digital Library, folder section6.4, files NOCTURNAL_SUNDIAL.max and EQUATORIAL SUNDIAL.max

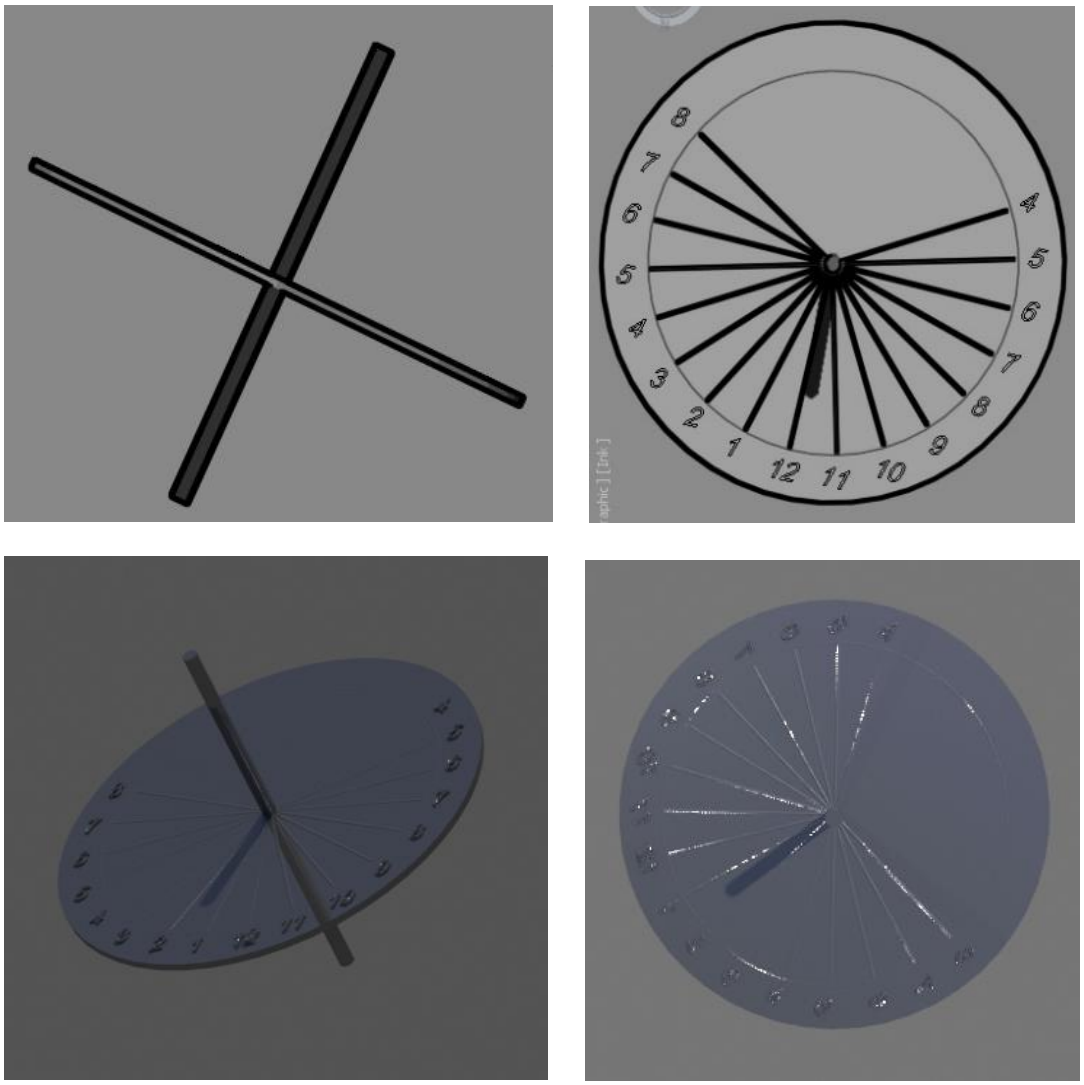


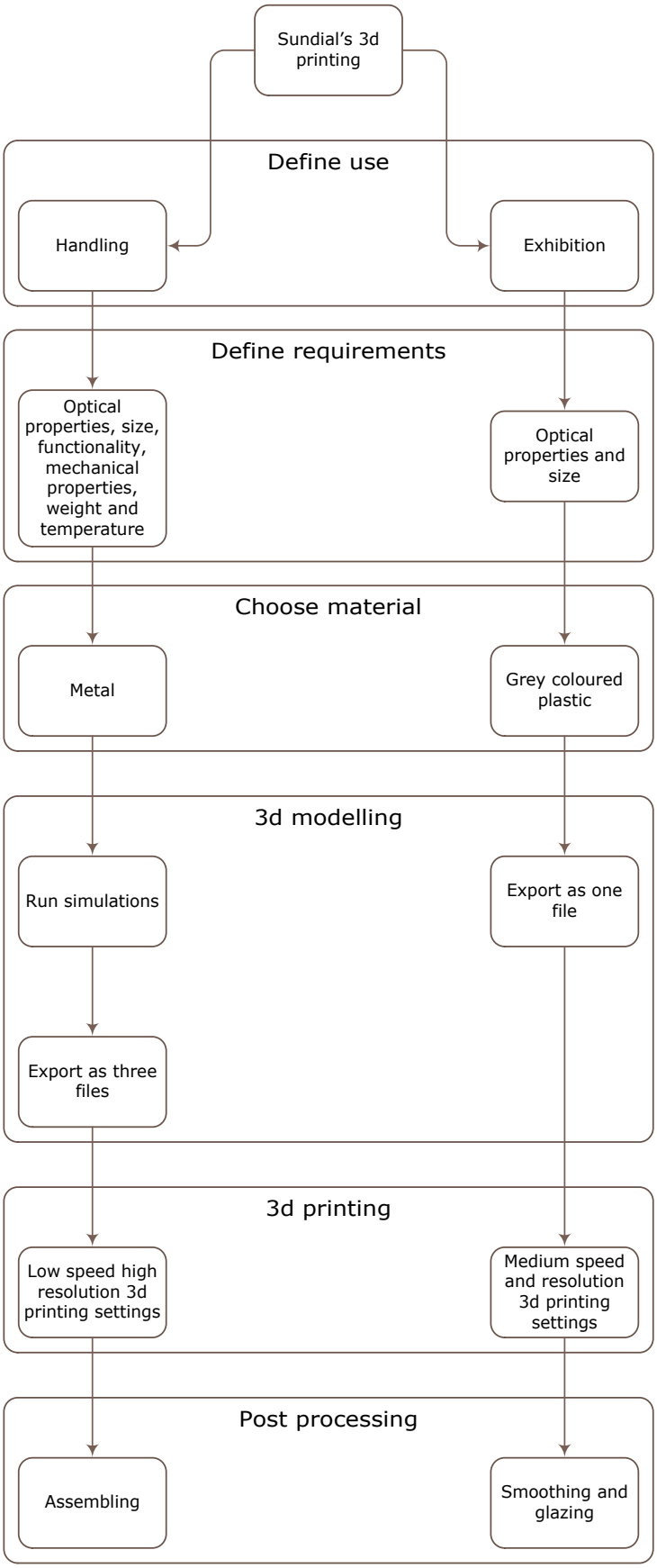
Figure 431: Renderings of the sundial. Equatorial sundial (Image author's own).

Finally, the sundial model can be 3d printed. The replica can be used in various ways, either within or outside the museum environment. It would be useful for display because it represents a complete version, which would be easier for the museum's visitors to understand. The replica would be a useful addition to handling sessions, because it will offer the opportunity not only to appreciate the object in its case, and understand its use via animations and still images, but also to handle and have an actual experience of its use. The requirements for the 3d printing project depend on the use of the replica. The replica as a handling session object should not only represent the appearance, as it happens in its exhibition use, but also its function, weight, temperature.

Considering the above, for handling sessions, the model should be printed with metal material (see section 2.3.2.5.3 for a discussion on 3d printing materials), resulting in a more convincing replica, in terms of temperature, weight, strength, optical properties and with a better representation of detail. The latter is of particular importance in order for the object to be functional because of the low relief detail. Simulations can be useful in testing the mechanical properties of the chosen material and the functionality of the sundial. In order to avoid problems in 3d printing, it is recommended to print the sundial in three parts (see Figure 412 for the nocturnal sundial assembly parts). This requires assembling of these parts after printing. On the other hand the model can be 3d printed in plastic, exported as one file and post processed in order to acquire the desired optical properties for exhibition purposes (Graph 51). From the available materials in shapeways[77], platinum and metallic plastic (alumide) are appropriate for the creation of the metal and plastic replica respectively.

Although 3d printing has found many applications in packaging industry it has not been used for storage and transportation of archaeological materials, apart from limited experimentations at experimental level (Sa *et al.*, 2012). It would be inappropriate to store the sundial in 3d printed packaging, even if the potential of designing easily such a package is tremendous, due to the lack of research evidence for the geometric design and the 3d printing materials. A flexible, foam like material, chemically inactive should be used in addition to monitoring the microclimate of the container in order to meet the requirements for the packaging of iron. Already developed 3d printing materials, such as the elasto plastic (shapeways, 2015), the Layfomm 40 Filament (Molitch-Hou, 2014) and the poly-flex material (Molitch-Hou, 2014) present similar properties and should be tested. Additionally, materials under development for protective helmets such as the microlattice (Thimmesch, 2014), may find application in artefacts packaging in the future.

[77] Shapeways is one of the leading companies in the field of 3d printing services (http://www.shapeways.com/)



Graph 51: Sundial's 3d printing (Graph author's own).

6.4.5 Conclusions

In order to proceed to virtual reconstruction as an approach towards treatment, it is crucial to question the reason of the virtual reconstruction. In this case study the material is in a poor conservation state that does not allow any form of human-object interaction with respect to remedial treatment. In general it is recommended to proceed to virtual reconstruction after values analysis, in order to define the goal of treatment and an ideal state of the object that should be revealed by remedial treatment, and/or visualised by virtual reconstruction.

6.5 Summary

In this chapter remedial conservation treatment, with a particular emphasis on fragments matching, replacement of lost material and re- and de-conservation, was considered. First, via comparative analysis of manual and semiautomatic processes for fragments' identification in terms of conservation objectives, and evaluation of the available software addressed their potential and limitations. Second, the use of 3d modelling and reproduction techniques for restoration was presented and evaluated, incorporating methodological aspects of traditional museum practices, which were never previously taken into consideration. Third, virtual reconstructions were used as an alternative to de- and re- conservation dilemmas, followed a concrete methodology for estimating the goal of treatment, and finally defining the role of virtual reconstruction in conservation. The emphasis and the main contribution of these experimentations is the implementation of 3d modelling in a way that befits conservation ethics and meets conservation needs, rather than the computational complexity of the reconstructions.

The following chapter summarises the experimental findings, reaches conclusions and presents recommendations regarding the application of digital techniques in conservation.

Chapter 7: Conclusions

7.1 Introduction

This thesis introduced the concept of conservation virtualization, and has explored and evaluated novel methodologies for preventive and remedial conservation of artefacts. Although the field of computer visualization is developing rapidly, and has already demonstrated successful applications in archaeology, the contribution to conservation science and practice has been limited, due to the absence of focused applied conservation research. This study aims to fill this gap, and bridge the conservation needs and the computational developments in the field of digital imaging and computer visualization. It has identified problematic aspects of practice and presented an overview of current approaches. It proposed novel digitization, imaging and documentation methodologies, and examined the nature and potential transformations introduced in the theoretical frameworks for conservation, as well as the role and impact of virtualization in traditional conservation practice. In particular, the study has sought to know whether the application of computational imaging, computer vision and digitization techniques can result in effective virtual visual analysis, and to what extend graphical 3d modelling and physical 3d reproductions can contribute to conservation treatment.

7.2 Virtualizing Conservation: a pragmatic approach

Of particular importance for the realization of conservation virtualization is the development of methodologies that are in accordance with conservation needs. The novel digitization techniques discussed throughout the thesis, either 2.5 d RTI visualizations or 3d models (PG), introduced for the first time in this thesis or applied and evaluated at a great extent, fulfil the above criteria. They are not static records, and effectively enable virtual visual analysis in different spectral areas, without physical interaction. Even if the artefact, in the state it was visualised, has been altered or does not exist anymore. This is advantageous for conservation applications, because physical access to artefacts may be limited, or may not be in a position to reveal crucial features for diagnostic examination and virtual analysis. Also, the constant alteration of

materials, a major aspect in conservation condition reporting, interventive and preventive treatment, can be significantly assisted by the visualizations of different states of an artefacts biography. Unnecessary handling is prevented; artefacts become more accessible and can be easily disseminated to the scientific community and the public.

Since the presentation of preliminary microscopic RTI results from the Classical-Hellenistic Derveni cemetery (Kotoula and Earl, 2011), awareness had been rapidly growing of the usefulness of microscopic RTI throughout the conservation community, followed by the application of these techniques in renowned institutions, such as the Straus Centre for Conservation and Technical Studies of the Harvard Art Museums (Schroer, 2012). The experimental microscopic dome developed in 2011 as part of this research is the first one of its kind. Since then, the field of microscopic RTI capture has been developed, in which led to the development of similar devices based on the same principles (Messier, 2014). Similarly, the trans illumination and irradiation RTI techniques, proposed for the first time in this research, have been used for the study of obscured writings, leading to the conclusion that they are the best methodological approach (Valergas, 2014). It is also notable that on-going research for the study of a 19th century canvas painting uses the before mentioned methodologies (Bennet, 2013). As far as the multispectral RTI methodologies are concerned, even if their feasibility has been proved since 2007, the applications in this study in a variety of material types, incorporating different spectral imaging techniques, provided the necessary case studies to demonstrate their utility to the cultural heritage community. In addition, the IR-RTI proposed in the Derveni Papyrus case study has been replicated for the study of Herculaneum Papyri as well. The proposed PG capture methodology also improved the quality of the photogrammetric reconstruction of Neolithic figurines in the National Archaeological Museum in Athens (Hamilakis, 2014).

Beyond digitization, the growing interest in computer applications in conservation, not only from the academic community but also from conservation professionals, either in museums or private practice, demonstrates the current trend towards alternative digital treatment. Since the initial discussion of the new possibilities for the replacement of lost material,

fragments matching and de-re conservation that this study embraces (Kotoula 2011), the field has considerably advanced (Arbace *et al.*, 2012; Powell, 2012; Beentjes and van der Molen, 2013; Davis, 2014; Horn and Monreal, 2012). Apart from the experimental findings, the issues discussed at a theoretical level, in particular the application of mixed reality approaches, such as projections, are now timely discussions, after case studies such as the restoration of faded Rothko's Harvard Murals using projection technology (Walsh, 2014).

It is highly likely that this current trend will evolve into a new sub-discipline of conservation and will contribute to the progress in the profession. Hence, there is a clear need for guidelines that will enable conservation professionals and researchers to successfully incorporate digital components in their practice and research.

7.3 Guidelines for practice

7.1.1 Virtual restoration

It is necessary to define the aims and purpose of virtual restoration. Virtual restoration can be used as an alternative to conventional operations and treatments, as a documentation strategy, as supportive material for treatment proposal and as an analysis tool.

In general, virtual restoration may take place in cases where the traditional methodology cannot lead to an acceptable result based on contemporary standards. Reasons not to proceed to conventional remedial treatment may be cost and size constraints, health and safety, material preservation, absence of necessary evidence or appropriate materials and techniques for the execution of conservation operations. Suggested reasons to proceed to virtual restoration may be the poor preservation of the material, which cannot withstand manual handling, dimensions (either too small or too large objects) that makes it extremely difficult to conventionally conserve/restore the artefact and uncertainty for the final outcome of remedial treatment. The conservation virtualisation allows the conservator to explore the various possible ideal states, by creating virtual objects representing different events in the object's biography.

In particular, replacement of lost material using 3d modelling and 3d reproduction technologies is proposed in case of incomplete artefacts, which fulfil one or more of the following criteria: too fragile, extreme dimensions, excessive original material lost or advanced difficulty of aesthetic restoration. The use of this methodology is however not recommended in case of extremely distorted material, because the filler needs to cover authentic parts. Also, it is not recommended for materials whose preservation is problematic, such as organics, and/or materials that can be easily contaminated, because the long lasting performance of 3d printing materials is still unknown. In that case, an alternative approach is to 3d print moulds, and then fabricate missing parts manually using materials with known long lasting performance. The available 3d modelling tools make the creation of such negative moulds trivial. Digital refitting is recommended in cases of extreme fragmentation, where manual reconstruction is extremely laborious, in case of fragments physically located in different collections worldwide, or in the case of poor preservation. When de-re restoration is considered, it is recommended to examine the option to virtually restore the object, in cases of fragile, rare objects of particular historical, archaeological and research value.

Virtual restoration may be considered as a documentation of treatment strategies in case of complex, long-term conservation projects. Virtual restoration is recommended as supportive material in treatment proposals in case of uncertainties and dilemmas, in order to assist defining an *ideal* state and the realistic goal of treatment. It can also be used as a guide in complex projects, in order to enable smoother execution of manual operations, or as a tool of analysis in order to provide evidence for conservation decisions, test hypotheses and justify treatment. The role of virtualization in conservation practice is summarised according to conservation needs in Table 28, proposing actions in relation to the particular characteristics of each project.

Table 28: The role of virtualization in conservation

Conservation needs		Action
Analysis and decision making	• Different conservation hypothesis • Problematic evidence for decision making • Objects with long biographies	Virtual restoration
Documentation	• Complex and long-term projects • Need to justify treatment	
Treatment	• Poor material preservation • Extreme dimensions • Lack of appropriate conservation materials and techniques	
Restoration	• Excessive material lost or difficult aesthetic restoration or poor material preservation or extreme dimensions	Model and 3d print missing parts
	• Excessive material lost or difficult aesthetic restoration or problematic material preservation (e.g. organics) or extreme dimensions	Model and 3d print moulds
Fragments identification	• Extreme fragmentation • Poor material preservation • Fragments located in different collections	Digital refitting
Re and de restoration	• Poor material preservation • Rare object • Archaeological and/or historical research value	Virtual reconstruction

7.1.2 Digitization

According to the nature of the artefact (optical properties, composition, materials and techniques of manufacture, preservation state, and size), the goal of digitization (examination and analysis, condition reporting, general

documentation, presentation and dissemination) and the available resources different strategies may be adopted. According to the size of the artefact or the area of interest normal, macroscopic and microscopic techniques may be used. Although the digitization techniques discussed throughout the thesis are non-invasive, the state of preservation influences the digitization strategy, so as to come in accordance with safe and safety regulations. For example unnecessary movement of the artefact should be avoided during data capture in case of poorly preserved objects. In addition, the material properties and composition not only set the research questions and the points of interest but also assist in the selection of the best digitization strategy.

An artefact may be digitised in various events during its museum lifetime (registration, research, before treatment, during treatment, after treatment, before exhibition, before loans, after loans, condition reporting, preservation, virtual visual analysis, online publication). Ideally each visualization should be reproducible so as to be useful for comparative analysis in the future, when the artefact will follow the inevitable deterioration, but the reproducibility of digitization is much more important when artefacts are visualised for condition reports, before and after treatment or loans. Although reprocessing datasets may assist significantly the comparative analysis of visualizations produced in different events in the objects biography, the best approach is to follow a meticulous metadata keeping strategy, including equipment (software, hardware, cameras, lighting, filters) used and set-up, quality and quantity of dataset captured and processing pipeline and settings. In the future the use of a standard 3D object may ensure the veracity of imaging for permanent recording and condition reporting. This idea follows the concept of photographic scales and colour separation charts used in two dimensional recording. Worth mentioning is that the use of auxiliary devices for capture, such as domes, increases significantly the reproducibility of digitization. This advantage can be added to other benefits of such devices, such as the speed of capture and processing.

Particular emphasis should be devoted to digitization events related to treatment, preservation, analysis, research and online publications. Digitization is a preventive conservation measure particularly helpful in case of artefacts that are deteriorating rapidly and their preservation is not ensured as well as in

cases of reburial. Digitization for online publication enriches museums websites and attracts the attention of the public while at the same time enhances research and encourages cooperation between experts. Pre and post treatment digitization is not only a successful documentation strategy but also enhances treatment monitoring and assists conservation decision making. Digitization as a tool for condition reporting assists the evaluation of conservation materials and techniques and enhances the methodology for the study of material's deterioration phenomena. When digitization is being used as a tool for research it provides opportunities to perform analysis that would be either impossible, unethical or too difficult using other means. The value of digitization for each event is summarised in Table 29.

Table 29: The value of digitization for major event in objects' museum life.

Event	Value
Treatment	Conservation documentation Treatment monitoring
Preservation	Preventive conservation
Condition reporting	Evaluation of conservation materials and techniques and study of materials' deterioration phenomena
Analysis and research	Advanced method for the analysis of artefacts
Online publication	Dissemination Accessibility

7.1.2.1 Use

Normal RTI should be used for the recording of surface and texture of objects, such as engraved or painted decoration and low relief details, for condition reporting, general documentation, presentation and dissemination. The nature of the artefact is irrelevant, although the curvature of the object will have an impact on the size, orientation and position of the area to be captured each time. Relatively flat objects of medium size are easier to capture. For example the normal RTI visualization of a coin or a canvas painting requires two RTI captures, a vase usually requires three captures, cylindrical objects six captures and complex petroglyphs or pictographs may require a series of RTI captures, depending on the geometry of the site

Micro-RTI should be applied for the recording of surface and texture at the microscopic level. Characteristic examples of successful micro-RTI applications are small coins with reflective material properties, such as gold or silver ones, and tiny fragments with surface features that can be interpreted as manufacture or use evidence.

IR-RTI should be used for the recording of subsurface texture for examination, analysis, condition reporting and presentation. The applicability of IR-RTI according the nature of the object follows the general knowledge from 2D multispectral imaging. For example, substrates of painted surfaces, preparatory drawings, obscured decoration elements, faded writings are among the features that can be visualised effectively using IR-RTI. IR-RTI can enhance the study of objects with saline encrustations but the results will be disappointing if the surface has been already destroyed by salts. UV-RTI should be used for the recording of subtle surface variations and documentation of previous repairs for examination, analysis, condition reporting and presentation of findings. Among the most interesting applications of UV-RTI is the study of museum biographies of objects. The technique is applicable to objects that can benefit from the application UV imaging techniques. In general, multispectral RTI techniques are useful for painted and inscripted flat surfaces and the study of previous repairs.

Trans-RTI should be applied for the recording of three-dimensionality of the transmittance properties of surfaces of translucent materials, including archival materials, canvas paintings, papyrus, and textiles for examination, analysis, condition reporting and presentation. It is highly recommended for painted or inscripted translucent flat surfaces and for the study of previous repairs and manufacture evidence.

The application of normal RTI is considered a prerequisite for the application novel RTI techniques. Nevertheless, each technique proved to be particularly helpful in the study of specific features. For example, as shown in table 30, the recording of transparent artefacts using RTI is not recommended. Similarly the application of multispectral and transmitted RTI in cases of complex geometry is difficult due to practical issues in capture and as a result the normal RTI technique should be preferred. Recommendation for the use of standard and novel RTI digitization techniques are summarised in Table 30. The techniques

are listed in increasing cost, including not only the equipment used in data capture but also the expertise needed for successful digitization.

Table 30: Recommendations for the use of standard and novel RTI digitization techniques. Key: green=highly recommended, blue=recommended, orange=low recommended, red=not recommended.

`

			RTI			
			Normal	Micro	Multispectral	Trans
			Increasing cost →			
FEATURES	Decoration	Engraved decoration				
		Painted decoration				
		Low relief detail				
	Size	Small size				
		Medium				
		Large				
	Optical properties	Translucent				
		Transparent				
	Geometry	Flat				
		Three dimensional				
		Complex				
	Use marks					
	Previous repairs					
	Manufacture evidence					

Normal PG should be used for 3d digitization of artefacts. It is recommended due to the ease of use and the low cost of equipment necessary for capture and processing. It should be used for general documentation purposes and analysis. It is recommended for the study of engraved and painted decoration, and low relief detail of medium and large objects, particularly for three dimensional objects of complex geometry.

Microscopic PG is proposed for capturing details of particular interest for examination, documentation and preservation purposes. It is recommended in cases of small size objects or specific areas of low relief detail and painted or engraved decoration for the study of use and manufacture evidence.

IR-PG is proposed for presentation of features beyond the visible in 3d space. It is particularly useful for the study of manufacture and use evidence, and previous repairs of painted three dimensional objects of medium size

Trans-PG is proposed for presentation of transmittance properties of materials in 3d space. . It is recommended in cases of small and medium size objects with painted decoration for the study of use and manufacture evidence, and previous repairs. It is only applicable in artefacts with a certain degree of translucency, meaning that translucent materials such as monochrome glass cannot be capture while painted canvas can be successfully recorded. Recommendations for the use of standard and novel PG digitization techniques are summarised in Table 31.

Table 31: Recommendations for the use of standard and novel PG digitization techniques. Key: green=highly recommended, blue=recommended, orange=low recommended, red=not recommended.

Features		PG			
		Normal	Trans	Micro	Multi-spectral
		Increasing cost →			
Decoration	Engraved decoration				
	Painted decoration				
	Low relief detail				
Size	Small size				
	Medium				
	Large				
Optical properties	Translucent				
	Transparent				
Geometry	Flat				
	3 dimensional				
	Complex				
Use marks					
Previous repairs					
Manufacture evidence					

7.1.2.2 Data Capture and Processing

The general recommended scheme for data capture follows the norm of the general to the specific. A useful strategy is to capture a frame covering the whole object, proceed to virtual visual analysis of the resulting file and identify areas of particular interest. Visual analysis with the naked eye, imaging and microscopic examination usually fail to reveal features of particular interest for the study of artefacts in comparison to RTI. For that reason it is recommended to identify the areas of interest based on RTI virtual visual analysis. Usually, images from low angles are particularly important for revealing low surface detail. It is advisable to focus on specific details using macroscopic lenses for medium size objects and/or microscopic techniques when studying small details.

Following the guidelines provided by CHI and AIC for capture and processing datasets, trans illumination/ irradiation and multispectral imaging is a prerequisite. For multispectral capture, considering that the data capture and processing is much more laborious, it is recommended that a set of multispectral static images be captured so as to identify, if applicable, the particular band that reveal the most interesting features. When analysing translucent material, it is important to consult trans illumination and irradiation images before capturing RTI datasets. The use of a light arm is necessary for the completion of data capture.

The parameters mentioned in the relevant section of this thesis should be taken under consideration for deciding the specific PG data capture methodology. The use of a soft box in order to control the reflections is recommended in normal photogrammetry. Reconstruction of PG datasets of translucent materials, such as glass, is not recommended. For capturing micro-PG datasets it is necessary to use appropriate equipment, such as USB microscopes.

In Tables 30 and 31 the techniques are listed in increasing cost, including not only the equipment used in data capture but also the expertise needed for successful digitization. In terms of novel PG techniques, transmitted PG is the easiest one to perform, taking under consideration that the only differentiation from the standard technique is the different lighting. Microscopic PG is more laborious and expensive, as it requires special equipment (USB microscope with specific features) and experience in its use. The multispectral technique is considered the most laborious, mainly due to the time for capturing a complete dataset and the expertise needed to use the UV-VIS-IR modified camera at a proficient level so as to capture a complete dataset. In terms of novel RTI techniques the micro RTI is considered the easiest to perform. Conservators are familiar with microscopes use and features and commercial devices are now available to assist micro-RTI capture. Multispectral RTI is more difficult, requires a good knowledge of multispectral imaging techniques and is more time consuming. Transmitted RTI techniques are considered the most laborious, with the exception of the use of a modified dome, which is not commercially available at the moment.

Experience in RTI and PG data capture and processing, photography and digital image processing are crucial for the successful application of the techniques. Similarly to conventional conservation practice, experienced professional are in a position to provide solutions to problems encountered, and take decisions which are of fundamental importance for the successful execution of the digitization projects. The training offered by CHI lasts eight days[78], but usually trainees are in a position to understand the techniques in one day workshop.

7.1.2.3 Viewing, virtual analysis

The use of the virtual examination tools is recommended, because of the advanced opportunities provided by virtual visual analysis, as demonstrated by their evaluation. Nevertheless, for an overall examination of an artefact and decision making for remedial treatment there is a need to perform conventional visual analysis. Due to the irreversible nature of conservation, the decisions should be taken after consulting all the available resources.

It is necessary to follow a concrete virtual analysis strategy, similar to conventional strategies, in order to use the tools to their full potential. A digital label should be attached to the digital file, which may include the metadata about the digitization technique (software and hardware used for the creation of the file) and the visualised artefact (accession number, museum, excavation, date of discovery, dating, typology, material and if applicable specific type of artefact). For example, for RTI visualizations the suggested metadata are listed below:

- Data capture method (rotation arm or a dome or the H-RTI method)
- Lighting (transmitted or reflected)
- Spectral area (visible lighting or IR or UV)
- Hardware (cameras and filters and lenses- microscopic level or macroscopic or normal)
- Measurements (an indication of scale, either scale bar or a given maximum dimension)

[78] http://culturalheritageimaging.org/What_We_Offer/Training/

- File creator and affiliation
- Date

A general structure of the recording of findings of virtual analysis may include four main types of comments; the characterization, interpretation, biography and general comments. The characterization comments include description of features observed, which were further analysed in the interpretation comments. The biography comments include features such as materials and manufacture technology, use, damage and previous intervention. Finally, the general comments provide the necessary space for descriptions and general assessment. The practice of adding comments on the digital artefact, (available solutions exist both for 3d models and RTI visualizations), results in the creation of an examination record rather than just a simple record of the artefact. This attributes extra values to the digitised artefact, and its uses are extended for the scientific community, museums, for organizational and administrative purposes and for the public.

7.1.3 Software and hardware

The use of high quality imaging equipment, powerful computers and professional pieces of software is preferred, because it minimises processing time and provides better results. Nevertheless it is not considered a prerequisite. The software and hardware needed for each technique is listed in Table 32.

Table 32: Photographic equipment and software needed for standard and novel RTI and PG digitization techniques.

TECHNIQUE	PHOTOGRAPHIC EQUIPMENT	SOFTWARE
RTI	CAMERA, TRIPOD, RTI TARGETS, FLASH, REMOTE TRIGGERS	RTI BUILDER, RTI VIEWER, DIGITAL IMAGE PROCESSING SOFTWARE
MULTISPECTRAL RTI	UV-VIS-IR MODIFIED CAMERA, FILTERS, TRIPOD, RTI TARGETS, RADIATION SOURCES, REMOTE TRIGGERS	
TRANS-RTI	CAMERA, TRIPOD, RTI TARGETS, FLASHES, REMOTE TRIGGERS, RTI ARM	
MICRO-RTI	MICROSCOPE EQUIPED WITH CAMERA, PEN LIGHT, RTI TARGET	RTI BUILDER, RTI VIEWER, MICROSCOPIC IMAGING SOFTWARE
PG	CAMERA, SOFT-BOX, TRIPOD, FLASHES	PG SOFTWARE, DIGITAL IMAGE PROCESSING SOFTWARE
TRANS-PG	CAMERA, FLASHES, TRIPOD	
MULTISPECTRAL PG	UV-VIS-IR MODIFIED CAMERA, FILTERS, TRIPOD, RADIATION SOURCES	
MICRO-PG	USB MICROSCOPE, STAND	PG SOFTWARE, DIGITAL IMAGE PROCESSING SOFTWARE, MICROSCOPIC IMAGING SOFTWARE

7.4 Recommendations for future research

The methodologies explored in this thesis initiate a discussion and lead to open questions for future research. The main areas of interest for future research are the following:

- *The development of auxiliary devices* for data capture is useful. For example, there is great potential in the development of a microscopic dome suitable for capturing either horizontal or vertical subjects at different magnifications. Minimum requirements, main components, additional features and proposed workflow, along with 3d model of the proposed design are located in the Appendix E1.

- *The development of software for processing and simultaneous analysis of visualizations.* Although the digitization options discussed throughout the thesis are advanced, a significant problematic aspect in their practical implementation is the absence of software able to integrate different visualizations. A complete assessment requires the use of various visualizations, for example in different spectral areas, magnifications, conservation state and creation using different techniques, considering that all the files refer to one artefact and conceptually form one entity. The separate analysis of all the different files is not synonymous with the simultaneous analysis. The latter provides a holistic approach to the virtual analysis. In such a virtual examination environment, it is crucial to identify the provenance of features and to document the interpretation process.

- *The enhancement of data management, online publication and collaborative research.* A proposed workflow for deposit and publication of RTI data includes the addition of a new type of file (bookshot), which is a snapshot specifically created as a visual representation of a current bookmark. The RTI dataset and files, as well as the bookshots, will be included in a repository available for free download. Each file will have its own DOI, so citing either the whole RTI or a specific bookshot will enhance publications and encourage a scientific dialogue over the outcomes of RTI. Online crowd annotations of RTI files may contribute towards a dialogue between cultural heritage professionals as well. Whilst the current annotation methods allow for multiple annotations for different users they do not provide a specific collaborative framework. Initial thoughts for the structure and use of a virtual collaborative visual RTI environment are located in the Appendix E2

- *Testing of 3d printing materials*. Considering that the existing 3d printing materials are new, and their long lasting performance in contact with authentic archaeological material is unknown, there is an urgent need for accelerative ageing tests so as to define whether or not it is safe to use them in close proximity with original artefacts.

- *Focused applied conservation research.* The further application of the proposed methodologies, focused on specific research questions, is proposed. Via these types of research projects valuable experience can be gained for the further development of techniques and methodological approaches towards conservation, while, at the same time, knowledge regarding artefacts can be significantly enriched.

List of references

3D COFORM (2013) *Annotation Scenario*. Available from: http://www.3d-coform.eu/index.php/scenarios/annotation-scenario [Accessed 16 November 2014].

Abel, R.L., Parfitt, S., Ashton, N., Lewis, S. G., Scott, B. and Stringer, C. (2011) Digital preservation and dissemination of ancient lithic technology with modern micro-CT. *Computers and Graphics*, 35 (4), 878–884. Available from: http://www.sciencedirect.com/science/article/pii/S0097849311000409 [Accessed 16 November 2014].

Abraham, E., Younus, A., El Fatimy, A., Delagnes, J., Nguéma, E. and Mounaix, P. (2009) Broadband terahertz imaging of documents written with lead pencils. *Optics Communications*, 282 (15), 3104-3107. Available from: http://www.sciencedirect.com/science/article/pii/S0030401809003927 [Accessed 16 November 2014].

Acute 3d (2013) *Turn photos into 3D models automatically with Smart3DCaptureTM*. Available from: http://www.acute3d.com/smart3dcapture [Accessed 20 January 2014].

Adán, A., Salamanca, S. and Merchán, P. (2012) A hybrid human–computer approach for recovering incomplete cultural heritage pieces. *Computers and Graphics*, 36 (1), 1–15. Available from: http://www.sciencedirect.com/science/article/pii/S009784931100149X [Accessed 16 November 2014].

Addison, A.C., Bryan, P. and Schmid, W. (2005) People and Technology: A Discussion about Heritage Documentation. Conservation Perspectives, *The GCI Newsletter*, 20 (3), 10–16. Available from: http://www.getty.edu/conservation/publications_resources/newsletters/pdf/v20n3.pdf [Accessed 16 November 2014].

Agisoft (2014) *Image-based 3D modeling. Make it with Agisoft PhotoScan*. Available from: http://www.agisoft.ru/ [Accessed 20 January 2014].

AIC (1994) *Core Documents-Code of Ethics*. Available from: http://www.conservation-us.org/about-us/core-documents/code-of-ethics#.VGi2vMk_jhA [Accessed 16 November 2014].

Alexopoulou, A., Kaminari, A., Panagopoulos, A. and Pöhlmann, E. (2013) Multispectral documentation and image processing analysis of the papyrus of tomb II at Daphne, Greece. *Journal of Archaeological Science*, 40 (2), 1242–1249. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440312004153 [Accessed 16 January 2013].

Allard, T. T., Sitchon, M., Sawatzky, R., and Hoppa, R. D. (2005) Use of Hand-held Laser Scanning and 3D Printing for Creation of a Museum Exhibit. IN: Mudge, M., Ryan, N. and Scopigno, R. (eds.) *VAST 2005: 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, 3rd Eurographics Workshop on Cultural heritage. ACM/EG VAST 2005, Short and Project Papers*. Pisa: Epoch-net. Available from: http://public-repository.epoch-net.org/publications/VAST2005/shortpapers/short3006.pdf [Accessed 16 November 2014].

Anderson, S.E. and Levoy, M. (2002) Unwrapping and visualizing cuneiform tablets. *IEEE Computer Graphics and Applications*, 22 (6), 82–88. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1046632andtag=1 [Accessed 16 January 2013].

Appelbaum, B. (2007) *Conservation treatment methodology*. Oxford: Butterworth-Heinemann/Elsevier.

Appelbaum, B. (2008) Conservation Treatment and the Custodian/Conservator Relationship. *CeROArt,* 2. Available from http://ceroart.revues.org/index445.html [Accessed 16 January 2014].

Applbaum, N. and Applbaum, Y.H. (2005) The Use of Medical Computed Tomography (CT) Imaging in the Study of Ceramic and Clay Archaeological Artifacts from the Ancient Near East. IN: Uda, M., Demortier, G. and Nakai, I. (eds.) *X-rays for archaeology*. Netherlands: Springer, 231-245. Available from:

http://link.springer.com/chapter/10.1007/1-4020-3581-0_17 [Accessed 16 November 2014].

Arbace, L., Sonnino, E., Callieri, M., Dellepiane, M., Fabbri, M., Iaccarino Idelson, A. and Scopigno, R. (2012) Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue. *Journal of Cultural Heritage*. 14 (4), 332-345. Available from: http://www.sciencedirect.com/science/article/pii/S1296207412001070 [Accessed 16 November 2014].

Arnold, D. and Geser, G. (2008) *The EPOCH research agenda for the applications of ICTs to cultural heritage*, Budapest: Archaeolingua.

Arnold, J.B. and McAllister, M.L.M. (1998) Artefact replication by stereolithography. *The International Journal of Nautical Archaeology*, 27 (2), 160–165. Available from: http://onlinelibrary.wiley.com/doi/10.1111/j.1095-9270.1998.tb00799.x/pdf [Accessed 16 November 2014].

Artal-Isbrand, P., Klausmeyer, P. and Murray, W. (2011) An evaluation of decorative techniques on a red-figure Attic vase from the Worcester Art Museum using reflectance transformation imaging (RTI) and confocal microscopy with a special focus on the "relief line." IN: Vandiver, P., Li, W., Sil, J., Reedy, C. and Frame, L. (eds.) *Materials issues in art and archaeology IX*. Boston, 29 November- 3 December 2011. Warrendale: Materials Research Society, 3–33.

Ashley-Smith, J. (1999) *Risk assessment for object conservation*. Oxford: Butterworth-Heinemann.

Ashley-Smith, J. (2000) Twenty first century conservation. *V&A conservation journal*, 34. Available from: http://www.vam.ac.uk/content/journals/conservation-journal/issue-34/twenty-first-century-conservation/ [Accessed 16 November 2014].

Ashley-Smith, J. (2009) The Basis of Conservation Ethics. IN: Richmond, A. and Bracker, A. (eds.) *Conservation: Principles, Dilemmas, and Uncomfortable Truths*. Oxford: Butterworth-Heinemann, 6–23.

Autodesk (2014) *3DS Max* [computer program]. Available from: http://www.autodesk.co.uk/products/3ds-max/overview [Accessed 17 November 2014].

Autodesk (2014) *Autodesk 123D.* Available from: http://www.123dapp.com/ [Accessed 20 January 2014].

Azhari, H. (2010) Special Imaging Techniques. IN: *Basics of Biomedical Ultrasound for Engineers*. New Jersey: John Wiley and Sons, 233–269.

Baade, B., Kerr-Allison, A. and Giaccai, J., (2012) Pursuit of the ideal effect: the materials and techniques of Henry Ossawa Tanner. IN: Marley, A. O. (ed.) *Henry Ossawa Tanner: modern spirit*. Philadelphia: Pennsylvania Academy of the Fine Arts, 157–166.

Bakraji, E., Boutros, N. and Abboud, R. (2013). Thermoluminescence (TL) dating of ancient Syrian pottery from six different archaeological sites. *Geochronometria*, 41 (1), 24-29.

Balas, C., Papadakis, V., Papadakis, N., Papadakis, A., Vazgiouraki, E., and Themelis, G. (2003) A novel hyper-spectral imaging apparatus for the non-destructive analysis of objects of artistic and historic value. *Journal of Cultural Heritage*, 4 (Supplement 1), 330–337. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207402012165 [Accessed 20 January 2014].

Baldia, C.M. and Jakes, K. A. (2007) Photographic methods to detect colourants in archaeological textiles. *Journal of Archaeological Science*, 34 (4), 519–525. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440306001233 [Accessed 16 January 2013].

Barazzetti, L., Binda, L., Scaioni, M., and Taranto, P. (2011) Photogrammetric survey of complex geometries with low-cost software: Application to the G1 temple in Myson, Vietnam. *Journal of Cultural Heritage*, 12 (3), 253–262. Available from:

http://linkinghub.elsevier.com/retrieve/pii/S1296207411000021 [Accessed 30 October 2012].

Barber, D. and Mills, J. (2011) *3D laser scanning for heritage*, 2nd edition. Swindon: English Heritage. Available from: https://www.english-heritage.org.uk/publications/3d-laser-scanning-heritage2/ [Accessed 30 October 2012].

Baribeau, R., Rioux, M. and Godin, G. (1995) Three-Dimensional Object Modeling. IN: Bearman, D. (ed.) *Multimedia computing and museums: selected papers from the Third International Conference on Hypermedia and Interactivity in Museums (ICHIM'95-MCN'95)*. San Diego, 9-13 October 1995. Pittsburgh: Archives and Museum Informatics, 170–176.

Barker, R. and Smithen, P. (2008) New art, new challenges and the changing face of conservation. IN: Marstine, J. (ed.) *New Museum Theory and Practice*. Chichester: John Wiley and Sons, Ltd, 86–104.

Barni, M., Pelagotti, A. and Piva, A. (2005) Image Processing for the Analysis and Conservation of paintings: opportunities and challenges. *IEEE Signal Processing Magazine*, 22(5), 141–144. Available from: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=1511835 [Accessed 30 October 2012].

Barov, Z. (1988) The reconstruction of a Greek vase: the Kyknos krater. *Studies in conservation,* 33 (4), 165–177.

Basballe, D.A. and Halskov, K. (2010) Projections on museum exhibits: engaging visitors in the museum setting. IN: Brereton, M. Viller, S. and Kraal, B. (eds.) *Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction*, Brisbane, 22 - 26 November 2010. New York: ACM, 80–87. Available from: http://doi.acm.org/10.1145/1952222.1952240 [Accessed 30 October 2012].

Baumann, R., Porter, D.C. and Seales, W.B. (2008) The use of micro-CT in the study of archaeological artifacts. IN: *Art 2008: Proceedings of the 9th International Conference on NDT of Art*, Jerusalem, 25–30 May 2008. Available

from: http://www.ndt.net/article/art2008/papers/244Seales.pdf [Accessed 30 October 2014].

Beale, G. (2014) *Representing Roman Statuary Using Computer Generated Images*. PhD Thesis. University of Southampton.

Beentjes, T. and van der Molen, R. (2013) 3D Scanning and Printing as Conservation Tools: an Innovative Treatment of a Vandalized Bronze Statue, The Thinker by Rodin. In Saunders, D. D., Strlič, M., Korenberg, C., Luxford, N. and Birkhölzer K. (eds.) *Lasers in the Conservation of Artworks IX*, London, 7-10 September 2011. London: Archetype Publications, 146-153.

Benazzi, S., Stansfield, E., Milani, C. and Gruppioni, G. (2009) Geometric morphometric methods for three-dimensional virtual reconstruction of a fragmented cranium: the case of Angelo Poliziano. *International Journal of Legal Medicine*, 123 (4), 333–344. Available from: http://dx.doi.org/10.1007/s00414-009-0339-6 [Accessed October 30, 2012].

Bennet, T. (2013) High-Resolution Multispectral Reflectance Transformation Imaging of a 19th Century British Painting. Paper presented at IEEE International Conference on Computational Photography, Cambridge, MA, USA, 19-21 April.

Berg, I. (2011) Exploring the Chaîne Opératoire of Ceramics through X-radiography. IN: Scarcella, S. (ed.) *Archaeological Ceramics: A Review of Current Research*. Oxford: Archaeopress, 57–63.

Bergamasco, M., Frisoli, A. and Barbagli, F. (2002) Haptics Technologies and Cultural Heritage Applications. IN: Proceedings of Computer Animation. Geneva, Switzerland, 19-21 June 2002, Washington: IEEE, 25–32. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=andarnumber=1017503andisnumber=21886 [Accessed 30 October 2012].

Bertrand, L., Robinet, L., Thoury, M., Janssens, K., Cohen, S. X. and Schöder, S. (2012) Cultural heritage and archaeology materials studied by synchrotron spectroscopy and imaging. *Applied Physics A*, 106 (2), 377–396. Available

from: http://www.springerlink.com/index/10.1007/s00339-011-6686-4 [Accessed 14 November 2014].

Bessou, M., Duday, H., Caumes, J. P., Salort, S., Chassagne, B., Dautant, A., ... and Abraham, E. (2012) Advantage of terahertz radiation versus x-ray to detect hidden organic materials in sealed vessels. *Optics Communications*, *285* (21), 4175-4179. Available from: http://www.sciencedirect.com/science/article/pii/S0030401812006554 [Accessed 16 November 2014].

Bevan, G., Lehoux, D. and Talbert, R. (2013) Reflectance Transformation Imaging of a "Byzantine" Portable Sundial. *Zeitschrift fur Papyrologie und Epigraphik*, 187, 221–229.

Biek, L. (1963). *Archaeology and the microscope*. New York: Praeger.

Bimber, O. Iwai, D., Wetzstein, G. and Grundhöfer, A. (2008) The Visual Computing of Projector-Camera Systems. *Computer Graphics Forum*, 27 (8), 2219–2245. Available from: http://onlinelibrary.wiley.com/doi/10.1111/j.1467-8659.2008.01175.x/pdf [Accessed 30 October 2014].

Biro, K.T., Durkovic, E. and Farkas-Szoke, S. (2011) Look Into the Objects: Why? Cultural Heritage Motivations of Neutron-Based Imaging Techniques. IN: Turbanti-Memmi, I. (ed.) *Proceedings of the 37th International Symposium on Archaeometry*, Siena, 13- 16 May 2008. Berlin: Springer, 365–370.

Boehler, W. and Marbs, A. (2004) 3D scanning and photogrammetry for heriatage applications: a comparison. IN: Anders Brandt, S. (ed.) *Geoinformatics 2004 Proc. 12th Int. Conf. on Geoinformatics Geospatial Information Research: Bridging the Pacific and Atlantic*, Gävle, 7-9 June 2004. Gävle: Gävle University Press, 291–298. Available from: http://fromto.hig.se/~bjg/geoinformatics/files/p291.pdf [Accessed 30 October 2014].

Böhler, W., Vicent, M. B., Heinz, G., Marbs, A. and Müller, H. (2004) High Quality Scanning and Modeling of Monuments and Artifacts. IN: *Proceedings of*

the FIG Working Week. The Olypic spirit in Surveying, Athens, 22-27 May 2004. Copenhagen: International Federation of Surveyors. Available from: https://www.fig.net/pub/athens/papers/wsa2/WSA2_2_Bohler_et_al.pdf [Accessed 30 October 2014].

Bonadies, S.D. (1994) Tomography of ancient bronzes. IN: Scott, D. A., Podany, J. and Considine, B. B. (eds.) *Ancient and Historic Metals: Conservation and Scientific Research*. Los Angeles: The Getty Conservation Institute, 75–84.

Borgia, G. C., Camaiti, M., Cerri, F., Fantazzini, P. and Piacenti, F. (2000) Study of water penetration in rock materials by nuclear magnetic resonance tomography: hydrophobic treatment effects. *Journal of cultural heritage*, 1 (2), 127–132. Available from: http://www.sciencedirect.com/science/article/pii/S1296207400001564 [Accessed 8 December 2012].

Bork, E. (2011) Money Laundering. IN: Cook, B. (ed.) *The British Museum and the Future of UK Numismatics*. London: The British Museum, 25–27.

Bortolot, V. J. (1994). Authentication by thermoluminescence. *Tribal Arts*, 1, 81-83.

Bradley, D. and Creagh, D. (eds.) (2006) *Physical Techniques in the Study of Art, Archaeology and Cultural Heritage*. Amsterdam: Elsevier Science.

Brandi, C. (1963) *Teoria del restauro*. Torino: Einaudi.

Brewster, S. A. (2005) The impact of haptic 'touching'technology on cultural applications. IN: Hemsley, J., Capellini, V. and Stanke, G. (eds.) *Digital Applications for Cultural Heritage Institutions*, Aldershot, England: Ashgate, 273-284. Available from: http://core.ac.uk/download/pdf/1393810.pdf [Accessed 28 January 2014].

Brewster, S.A. (2005) The impact of haptic "touching" technology on cultural applications. IN: Hemsley, J. Cappellini, V. and Stanke, G. (eds.) *Digital applications for cultural heritage institutions*. London: Ashgate, 273–284.

Brill, T.B. (1980) *Light: its interaction with art and antiquities*. New York: Plenum Publishing Corporation.

Brognara, C. et al., 2013. Edge Detection on Polynomial Texture Maps. IN: Petrosino, A. (ed.) *Image Analysis and Processing – ICIAP 2013 SE - 49. Lecture Notes in Computer Science*. Berlin Heidelberg, Springer, 482–491. Available at: http://dx.doi.org/10.1007/978-3-642-41181-6_49 [Accessed 5 June 2014].

Brown, B. J., Toler-Franklin, C., Nehab, D., Burns, M., Dobkin, D., Vlachopoulos, A., Doumas, C., Rusinkiewicz, S. and Weyrich, T. (2008) A System for High-Volume Acquisition and Matching of Fresco Fragments: Reassembling Theran Wall Paintings. *ACM Transactions on Graphics (TOG)*, 27 (3), 84-100. Available from: http://doi.acm.org/10.1145/1399504.1360683 [Accessed 30 October 2012].

Brown, D. H. (2002) *Pottery in Medieval Southampton: c 1066-1510*. York: Council for British Archaeology

Bugani, S., Camaiti, M., Morselli, L., Van de Casteele, E. and Janssens, K. (2008) Investigating morphological changes in treated vs. untreated stone building materials by x-ray micro-CT. *Analytical and Bioanalytical Chemistry*, 391 (4), 1343–1350. Available from: http://link.springer.com/article/10.1007%2Fs00216-008-1946-7 [Accessed 8 December 2012].

Bugani, S., Camaiti, M., Morselli, L., Van de Casteele, E. and Janssens, K. (2009) Study on the impregnation of archaeological waterlogged wood with consolidation treatments using synchrotron radiation microtomography. *Analytical and bioanalytical chemistry*, 395 (7), 1977–85. Available from: http://link.springer.com/article/10.1007/s00216-009-3101-5 [Accessed 8 December 2012].

Buoso, M.C., Ceccato, D. and Zafiropoulos, D. (2009) False-Color Infra Red Photography in the Identification of Pigments Used for a Late 13th Century Illuminated Manuscript. *Applied and Interdisciplinary Physics Instrumentation*, 8545, 153-154. Available from:

http://www.lnl.infn.it/~annrep/read_ar/2009/contributions/pdfs/153_B_113_B08.pdf [Accessed 8 December 2012].

Bussiere, P. O., Gardette, J. L. and Therias, S. (2014) Photodegradation of celluloid used in museum artifacts. *Polymer Degradation and Stability*, 107, 246-254. Available from: http://www.sciencedirect.com/science/article/pii/S0141391014001219 [Accessed 28 November 2014].

Butler, M. and Neave, P. (2008) Object appreciation through haptic interaction. In Hello! Where are you in the landscape of educational technology? IN: Atkinson, R. and McBeath, C. (eds) *ASCILITE 2008 Melbourne*, Melbourne, 30 November – 3 December 2008. Burwood: Deakin University, 133–141. Available from: http://www.ascilite.org.au/conferences/melbourne08/procs/butler-m.pdf [Accessed 8 December 2012].

Butler, P., Chakraborty, P. and Ramakrishan, N. (2012) The Deshredder: A visual analytic approach to reconstructing shredded documents. IN: Santucci, G. and Ward, M. (eds.) *IEEE Conference on Visual Analytics Science and Technology 2012*, Seattle, 14-19 October 2012. New York: IEEE, 113–122. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6400560 [Accessed 8 November 2012].

Buys, S. and Oakley, V. (1996) *The Conservation and Restoration of Ceramics*, 2nd edition. London: Butterworth-Heinemann/Elsevier

Caine, M. and Magen, M. (2011) Pixels and Parchment: The Application of RTI and Infrared Imaging to the Dead Sea Scrolls. IN: Dunn, S., Bowen, J. and Ng, K. (eds.) *EVA London 2011: Electronic Visualisation & the Arts*, London, 6-8 July 2011. Swindon: British Computer Society. Available from: http://ewic.bcs.org/upload/pdf/ewic_ev11_s8paper2.pdf [Accessed 29 November 2013].

Callieri, M., Cignoni, P., Ganovelli, F., Montani, C., Impoco, G., Pingi, P., Ponchio, F. and Scopigno, R. (2005) Restoring David using 3D. *Potentials, IEEE*,

23 (5), 4-7. Available from: http://iplab.dmi.unict.it/publication/366 [Accessed 29 November 2013].

Camaiti, M., Casieri, C., De Luca, F., Fantazzini, P. and Terenzi, C. (2007) The use of portable single-sided relaxometry and laboratory imaging NMR devices in stone conservation. *Studies in conservation*, 52 (1), 37-49.

Candlin, F. (2004) Don't Touch! Hands Off! Art, Blindness and the Conservation of Expertise. *Body and Society*, 10 (1), 71–90. Available from: http://bod.sagepub.com/cgi/doi/10.1177/1357034X04041761 [Accessed 29 November 2013].

Candlin, F. (2006) The Dubious Inheritance of Touch: Art History and Museum Access. *Journal of Visual Culture*, 5 (2), 137–154. Available from: http://vcu.sagepub.com/cgi/doi/10.1177/1470412906066906 [Accessed 29 November 2013].

Caple, C. (2000) *Conservation skills: Judgement, Method and Decision making*. London: Routledge.

Caple, C. (2006) *Objects: Reluctant Witnesses to the Past*. London: Routledge.

Caple, C. (2009) The Aims of Conservation. IN: Richmond A. and Bracker, A. L. (eds.) *Conservation: Principles, Dilemmas, and Uncomfortable Truths*. Oxford: Butterworth-Heinemann, 25–31.

Caple, C. (2011) The history and an introduction to preventive conservation. IN: Caple, C. (ed.) *Preventive Conservation in Museums*. London: Routledge, 1–18.

Carroll, M., Tomlinson, R., Wachowiak, M. and Webb, E. K. (2013) MapArt OpenSource Viewer: A Layered Solution for Viewing Scientific Imagery. IN: Burns, P. (ed.) *Archiving 2013*, Washington, April 2013. Springfield: Society for Imaging Science and Technology, 259–263. Available from: http://www.ingentaconnect.com/content/ist/ac/2013/00002013/00000001/art00055 [Accessed 29 November 2014].

Casali, F., Morigi, M.P., Bettuzzi, M. and Brancaccio. R. (2005) *X-ray computed tomography of an ancient large globe*. Available from: http://www.irt.unibo.it/en/alma-heritage-science/case-studies/image-structure-and-materials-conservation-and-restoration/x-ray-computed-tomography-of-an-ancient-big-globe [Accessed November 29, 2014].

Casaril, G., Gobbi, A., Repola, L., Sassetti, C. and Vignone., F. (2006) From digital model to real model: the study and recomposition project of the opus sectile floor in the chapel of Santa Restituta, at the archaeological site of San Vincenzo al Volturno, Isernia. IN: Guido, B. and Guido, D. (eds.) *Pavimentazioni storiche: uso e conservazione: atti del convegno di studi*, Bressanone, 11-14 July 2006. Marghera-Venezia: Arcadia ricerche, 481–490.

Castriota, B. and Serotta, A. (2011) Reflectance Transformation Imaging Training at the Conservation Center. *Newsgram: News in brief from the Conservation Center*, 4, 1–2. Available from: http://www.nyu.edu/gsas/dept/fineart/pdfs/publications/Newsgram4_RTI.pdf [Accessed 29 November 2014].

Caulton, T. (1998) *Hands-On Exhibitions: Managing Interactive Museums and Science Centres*. Florence: Routledge. Available from: http://site.ebrary.com/lib/soton/docDetail.action?docID=10016987 [Accessed 29 November 2014].

Caumes, J., Younus, A., Salort, S., Chassagne, B., Recur, B., Ziéglé, A., Dautant, A. and Abraham, E. (2011). Terahertz tomographic imaging of XVIIIth Dynasty Egyptian sealed pottery. *Applied Optics*, 50 (20), 3604-3608

Celani, G., Cancherini, L., Jardini, A., Oliveira, M., Lopes da Silva, J. V., and Piccoli, V. (2009) 3D digitation of museum sculptures for model-making purposes: difficulties and possible solutions. *Anais do VRAP,* 1–4. Available from: http://www.fec.unicamp.br/~lapac/papers/celani-et-al2009.pdf [Accessed 29 November 2014].

Cesarani, F., Martina, M. C., Grilletto, R., Boano, R., Roveri, A. M. D., Capussotto, V., Giuliano, A., Celia, M. and Gandini, G. (2004) Facial reconstruction of a wrapped Egyptian mummy using MDCT. *American Journal*

of Roentgenology, 183 (3), 755–758. Available from: http://www.ajronline.org/doi/abs/10.2214/ajr.183.3.1830755 [Accessed 29 November 2014].

Chankow, N. (2012) Neutron Radiography. IN: Omar, M. (ed.) *Nondestructive Testing Methods and New Applications*. Rijeka: InTech, 73–100. Available from: http://www.intechopen.com/books/nondestructive-testing-methods-and-new-applications/neutron-radiography [Accessed 16 November 2014].

Chatterjee, H. (ed.) (2008) *Touch in Museums: Policy and Practice in Object Handling*. Oxford: Berg Publishers

Chatzidakis, M. (2001) *Design of a Computer-aided Conservation Documentation System*, Master of Science Thesis, University of Crete. Available from: www.ics.forth.gr/isl/publications/paperlink/xatzidaki.pdf [Accessed 29 November 2014].

Clark, A. J., Elston, M. and Hart, M. L. (2002) *Understanding Greek vases: a guide to terms, styles, and techniques*. Los Angeles: Getty Publications.

Clavir, M. (2002) Preserving What Is Valued. Vancouver: UBC Press. Available from: http://site.ebrary.com/lib/soton/docDetail.action?docID=10056070 [Accessed 29 November 2014].

Cnudde, V., Dierick, M., Vlassenbroeck, J., Masschaele, B., Lehmann, E., Jacobs, P. and Van Hoorebeke, L. (2007) Determination of the impregnation depth of siloxanes and ethylsilicates in porous material by neutron radiography. *Journal of Cultural Heritage*, 8 (4), 331–338. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207407000994 [Accessed 18 January 2013].

Cohen, F., Zhang, Z. and Jeppson, P. (2010) Virtual reconstruction of archaeological vessels using convex hulls of surface markings. IN: *IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops* (CVPRW), *San* Francisco, 13-18 June 2010. Washington: IEEE, 55–61. Available from:

http://www.sciencedirect.com/science/article/pii/S0097849312001707 [Accessed 17 November 2013].

Conroy, G.C. and Vannier, M.W. (1984) Non-invasive three-dimensional computer imaging of matrix-filled fossil skulls by high-resolution computed tomography. *Science*, 226 (4673), 456–458. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17799939 [Accessed 17 November 2013].

Conti, A. (2007) *A history of the restoration and conservation of works of art.* Oxford: Butterworth-Heinemann.

Cook, R. M. (1997) *Greek painted pottery*, 3rd edition. New York: Routledge.

Corbett, P.E. (1965) Preliminary Sketch in Greek Vase-Painting. *The Journal of Hellenic Studies*, 85, 16–28. Available from: http://www.jstor.org/stable/628804 [Accessed 18 January 2013].

Cornelius, F.D. (1977) Correspondence: Transmitted infrared photography. *Studies in conservation*, 22 (1), 42.

Corrado, E. and Moulaison, H. (2014) *Digital preservation for libraries, archives, and museums*. Maryland: Rowman & Littlefield

Corsini, M., Dellepiane, M., Callieri, M. and Scopigno, R. (2006) Reflection Transformation Imaging on Larger Objects: an Alternative Method for Virtual Representations. IN: Forte, M. and Campana, S. (eds.) *From Space to Place, Proccedings of the 2nd International Conference on Remote sensing in Archaeology*, *BAR International Series 1568,* Rome, 4-7 December 2006. Oxford: Archaeopress, 407-412.

Cosma, C., Benea, V., Timar, A., Barbos, D. and Paunoiu, C. (2006) Preliminary dating results for ancient ceramics from Romania by means of thermoluminescence. *Radiation Measurements*, 41 (7-8), 987-990.

Costain, C. (2011) Framework for preservation of museums collections. IN: Caple, C. (ed.) *Preventive Conservation in Museums*. London: Routledge, 23–38.

Costanza, E. Jewell, M., Moreau, L., Earl G., and Frankland, T. (2013) *PoN:PATINA of Notes*. Available from: https://tina.ecs.soton.ac.uk/djangopon/research/ [Accessed 17 November 2013].

Creatz3D (2015) *3D Printing post processes.*Available from: www.creatz3d.com [Accessed 20 January 2015]

Cronyn, J.M. (2003) *The elements of archaeological conservation*. London and New York: Routledge.

Cucci, C., Picollo, M. and Vervat, M. (2012) Trans-illumination and trans-irradiation with digital cameras: Potentials and limits of two imaging techniques used for the diagnostic investigation of paintings. *Journal of Cultural Heritage*, 13 (1), 83–88. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207411000653 [Accessed 17 December 2012].

Cultural Heritage Imaging (2011) *Guide to highlight image processing*. Available from: http://culturalheritageimaging.org/What_We_Offer/Downloads/rtibuilder/RTI_hlt_Processing_Guide_v14_beta.pdf [Accessed 3 April 2012].

Cultural Heritage Imaging (2012) *Reflectance Transformation Imaging (RTI).* Available from: http://culturalheritageimaging.org/Technologies/RTI/ [Accessed 18 January 2013].

Cultural Heritage Imaging (2013a) *Digital Lab Notebook*. Available from: http://culturalheritageimaging.org/Technologies/Digital_Lab_Notebook/index.html [Accessed 20 January 2014].

Cultural Heritage Imaging (2013b) *Guide to RTIViewer, version 1.1.* Available from: http://culturalheritageimaging.org/What_We_Offer/Downloads/rtiviewer/RTIViewer_Guide_v1_1.pdf [Accessed 2 July 2014].

Cultural Heritage Imaging (2013c) *Guide to highlight image capture. Document version 2.0*. Available from:

http://culturalheritageimaging.org/What_We_Offer/Downloads/RTI_Hlt_Capture_Guide_v2_0.pdf [Accessed 17 November 2014].

Dahm, K. (2010) The stylus revealed: A metalpoint identification study of fifteenth-and sixteenth-century Italian drawings in the Metropolitan Museum of Art. *The Paper Conservator*, 28 (1), 75–86. Available from: http://www.tandfonline.com/doi/pdf/10.1080/03094227.2004.9638642 [Accessed July 2, 2014].

Dalsgaard, P. and Halskov, K. (2011) 3D Projection on Physical Objects: Design Insights from Five Real Life Cases. IN Tan, D., Fitzpatrick, G., Gutwin, C. Begole, B. and Kellogg W. A. (eds.) *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, Vancouver, 7-12 May 2011, New York: ACM, 1041–1050. Available from: http://dl.acm.org/citation.cfm?id=1979097 [Accessed July 2, 2014].

Daniilia, S., Minopoulou, E., Demosthenous, F. D. and Karagiannis, G. (2008) A comparative study of wall paintings at the Cypriot monastery of Christ Antiphonitis: one artist or two? *Journal of Archaeological Science*, 35 (6), 1695–1707. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440307002282 [Accessed 16 January 2013].

Davis, B. (2014) Practical project using 3d printing -17th century Yixing loose ring vase. Paper presented at Tape and Spillage: Interventive treatment in a Preventive Climate, ICON Ceramics and Glass meeting, York, 16-17 May.

Davis, J. (2012) An excavated lead sundial. *BSS Bulletin*, 24 (IV), 18–20. Available from: http://www.flowton-dials.co.uk/wp-content/uploads/2013/07/Excavated-lead-dial-Bull-24iv.pdf [Accessed 17 November 2014].

Davison, S. (2003) *Conservation and Restoration of Glass*, 2nd edition. Oxford: Butterworth-Heinemann.

De Reu, J., Plets, G., Verhoeven, G., De Smedt, P., Bats, M., Cherretté, B., De Maeyer, W. Deconynck, J., Herremans, D., Laloo, P., Van Meirvenne, M. and De

Clercq, W. (2012) Towards a three-dimensional cost-effective registration of the archaeological heritage. *Journal of Archaeological Science*, 40 (2), 1–14. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440312003949 [Accessed 8 November 2014].

De Smet, P. (2008) Reconstruction of ripped-up documents using fragment stack analysis procedures. *Forensic science international*, 176 (2-3), 124–136. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17869040 [Accessed 28 January 2013].

Desvallées, A. and Mairesse, F. (2010*) Key Concepts of Museology*. Paris: Armand Colin.

Digitali, Invasioni Digitali / Digital Invasions (2014) *Museums and the Web 2013*. Available from: http://mwf2014.museumsandtheweb.com/paper/invasioni-digitali-digital-invasions-co-creation-of-cultural-value/ [Accessed 10 March 2015].

Dooijes, R. and Nieuwenhuyse, O.P. (2009) Ancient repairs in archaeological research: a Near Eastern perspective. IN: Ambers, J., Higgit, C., Harrison, L. and Saunders, D. (eds.) *Holding it all together: Ancient and Modern Approaches to Joining, Repair and Consolidation*, London, 21-22 February 2008. London: Archetype, 8–12.

Douma, M. (2008*) Pigments through the Ages: Infrared (IR) light: Infrared False Color*. Available from: http://www.webexhibits.org/pigments/intro/ir.html [Accessed 19 January 2014].

Drenth, E. and Mom, V. (2009) Continuity and change: on a computer-aided classification of Late Neolithic and Early Bronze Age pottery from the Netherlands. IN: Frischer, B., Crawford, J. and Koller, D. (eds.) *Making history interactive. Computer Applications and Quantitative Methods in Archaeology (CAA): Proceedings of the 37th International Conference*, *BAR International Series 2079*, Williamsburg, 22-26 March 2009. Oxford: Archaeopress. Available from:

http://www.caa2009.org/articles/Mom_Drenth_Contribution_245_final.pdf [Accessed 19 January 2014].

Druzik, J. (2004) Illuminating Alternatives: Research in Museum Lighting, *Conservation Perspectives. GCI Institute Newsletter*, 19 (1). Available from: http://www.getty.edu/conservation/publications_resources/newsletters/19_1/news_in_cons1.html [Accessed January 19, 2014].

Duffy, S. (2010) Polynomial texture mapping at Roughting Linn rock art site. IN: Mills, J. P., Barber, D. M., Miller, P.E. and Newton, I. (eds.) *Proceedings of the ISPRS Commission V Mid-Term Symposium: Close Range Image Measurement Techniques*, Newcastle upon Tyne, 21-24 June 2010, 213–217. Available from: http://www.isprs.org/proceedings/XXXVIII/part5/papers/159.pdf [Accessed January 19, 2014].

Eagleton, C. (2005) Clocks and timekeeping. IN: Glick, T. F., Livesey, S. J. and Wallis, F. (eds.) *Medieval Science, Technology, and Medicine: An Encyclopedia*. New York: Routledge, 127–130.

Earl, G., Basford, P., Bischoff, A., Bowman, A., Crowther, C., Dahl, J., Hodgson, M., Isaksen, L., Kotoula, E., Martinez, K., Pagi, H. and Piquette, K. E. (2011) Reflectance Transformation Imaging Systems for Ancient Documentary Artefacts. IN: Dunn, S., Bowen, J. P. and Ng K. (eds.) *EVA London 2011: Electronic Visualisation & the Arts,* London, 6 - 8 July 2011. Swindon: British Computer Society. Available from: http://ewic.bcs.org/upload/pdf/ewic_ev11_s8paper3.pdf [Accessed 19 January 2014].

Earl, G., Beale, G., Happa, J., Williams, M., Turley, G., Martinez, K. and Chalmers, A. (2009) A re-painted amazon. IN: Seal, A., Keene, S. and Bowen, J. (eds.) *EVA London 2009: Electronic Visualisation & the Arts,* London: 6 - 8 July 2009. Swindon: British Computer Society, 20–29. Available from: http://www.bcs.org/upload/pdf/ewic_ev09_s1paper3.pdf [Accessed 19 January 2014].

Earl, G., Beale, G., Mmartinez, K. (2010) Polynomial Texture Mapping and related imaging technologies for the recording, analysis and presentation of

archaeological materials. IN: Mills, J. P., Barber, D. M., Miller, P.E. and Newton, I. (eds.) *Proceedings of the ISPRS Commission V Mid-Term Symposium: Close Range Image Measurement Techniques*, Newcastle upon Tyne, 21-24 June 2010, ISPRS, 218–223. Available from: from: http://www.isprs.org/proceedings/XXXVIII/part5/papers/227.pdf [Accessed 19 January 2014].

Earl, G., Martinez, K. and Malzbender, T. (2010) Archaeological applications of polynomial texture mapping: analysis, conservation and representation. *Journal of Archaeological Science*, 37 (8), 2040–2050. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440310001093 [Accessed 19 January 2014].

Easton, R.L.J., Knox, K.T. and Christens-Barry, W.A. (2003) Multispectral Imaging of the Archimedes Palimpsest. IN: *32nd Applied Image Pattern Recognition Workshop (AIPR 2003): Image Data Fusion*, Washington: 15-17 October 2003, Los Alamitos: IEEE, 111–116.

Ebert, L.C., Thali, M.J. and Ross, S. (2011) Getting in touch - 3D printing in Forensic Imaging. *Forensic Science International*, 211 (1-3), 1–6. Available from: http://www.sciencedirect.com/science/article/pii/S037907381100209X [Accessed 8 January 2013].

Ebinger-Rist, N., Peek, J. and Stelzner, F.G. (2011) Computed tomography: a powerful tool for non-destructive mass documentation of archaeological metals. IN: Mardikian P. (eds.) *Metal 2010 : proceedings of the interim meeting of the ICOM-CC Metal Working Group*, Charleston, 11-15 October 2010. Charleston: Clemson University, 342–347.

ECCO (2002) *Professional Guidelines, Article I: Definition of the Conservator-Restorer.* Available from: http://www.ecco-eu.org [Accessed 1 December 2011].

Echavarria, K. R., Theodoridou, M., Georgis, C., Arnold, D., Doerr, M., Stork, A. and Serna, S. P. (2012). Semantically rich 3D documentation for the preservation of tangible heritage. IN: Arnold, D., Kaminski, J., Niccolucci, F. and Stork, A. (eds.) *VAST: International Symposium on Virtual Reality, Archaeology*

and Intelligent Cultural Heritage, Brighton, 19-21 November 2012. Aire-la-Ville: Eurographics Association, 41-48. Available from: http://culturalinformatics.org.uk/files/papers/SemanticallyRich3D2012.pdf [Accessed 20 January 2014].

Elhabian, S., Rara, H. and Farag, A. (2011) On the use of hemispherical harmonics for modeling images of objects under unknown distant illumination. In Hadžialić, M., Behlilović, N. and Zovko-Cihlar, B. (eds.) *IEEE ICIP2011: 18th IEEE International Conference on Image Processing*, Brussels, 11-14 September 2011. Brussels: IEEE, 1109–1112. Available from: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6094293 [Accessed 20 January 2014].

Elston, M. (1990) Technical and Aesthetic Considerations in the Conservation of Ancient Ceramic and Terracotta Objects in the J. Paul Getty Museum: Five Case Studies. *Studies in conservation*, 35 (2), 69–80.

English Heritage (2006) *Guidelines on the X-radiography of archaeological metalwork*. Swinton: English Heritage Publications. Available from: https://www.english-heritage.org.uk/publications/x-radiography-of-archaeological-metalwork/ [Accessed 20 January 2014].

Eos Systems (2014) *Photo Modeler Scanner*. Available from: http://www.photomodeler.com/ [Accessed 20 January 2014].

EPPoSS (2008) *Internet of Things in 2020*. Available from: http://www.smart-systems-integration.org/public/internet-of-things [Accessed 20 November 2014].

Eren, G. (2010) *3D scanning of transparent objects*, PhD Thesis, Université de Bourgogne. Available from: https://tel.archives-ouvertes.fr/file/index/docid/584061/filename/these_A_EREN_Gonen_2010.pdf [Accessed 20 November 2014].

Evans, B. (2012). *Practical 3D printers*. New York: Apress.

Faigenbaum, S., Sober, B., Shaus, A., Moinester, M., Piasetzky, E., Bearman, G., Cordonsky, M. and Finkelstein, I. (2012). Multispectral images of ostraca:

acquisition and analysis. *Journal of Archaeological Science*, 39 (12), 3581–3590. Available from: http://linkinghub.elsevier.com/retrieve/pii/S030544031200252X [Accessed 16 January 2013].

Falck, H.W. and Halskov, K. (2013) Towards a framework for projection installations. IN: Ojala, T. (ed.) *PerDis 2013: Proceedings : 2nd ACM International Symposium on Pervasive Displays*, Mountain View, California, 4-5 June 2013, New York: ACM, 67-72. Available from: http://dl.acm.org/citation.cfm?doid=2491568.2491583 [Accessed 16 January 2014].

Fanti, G., Schwortz, B., Accetta, A., Botella, J. A., Buenaobra, B. J., Carreira, M., ... and Zugibe, F., 2005. Evidences for testing hypotheses about the body image formation of the Turin Shroud. Paper presented at the Third Dallas International Conference on the Shroud of Turin. Dallas, Texas, 8-11 September. Available from: http://www.ubthenews.net/topics/documents/2005ComprehEval.pdf [Accessed 28 January 2013].

Fantini, M., de Crescenzio, F., Persiani, F., Benazzi, S. and Gruppioni, G. (2008) 3D restitution, restoration and prototyping of a medieval damaged skull. *Rapid Prototyping Journal*, 14 (5), 318–324. Available from: http://www.emeraldinsight.com/10.1108/13552540810907992 [Accessed 28 January 2013].

Fell, V. and Watson, J. (2008). *Investigative conservation*. Swindon: English Heritage. Available from: https://www.english-heritage.org.uk/publications/investigative-conservation/ [Accessed 28 January 2013].

Ferguson, J. (2010) *Designing Experimental Research in Archaeology: Examining Technology through Production and Use*. Boulder: University Press of Colorado. Available from: http://site.ebrary.com/lib/soton/docDetail.action?docID=10389934 [Accessed 28 January 2013].

Fischer, C. and Kakoulli, I. (2006) Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications. *Reviews in Conservation*, 7, 3-16.

Fisher, P. and Norman, K.(1987) Anglo-Saxon glass claw beakers. *Studies in conservation*, 32(2), 49–58.

Foecke, T., Ma, L., Russell, M.A., Conlin, D.L. and Murphy, L.E. (2010) Investigating archaeological site

formation processes on the battleship USS Arizona using finite element analysis. *Journal of Archaeological Science* 37 (5): 1090–1101. Available from: http://www.sciencedirect.com/science/article/pii/S03 [Accessed 5 October 2014]

Fotakis, C., Anglos, D., Zafiropulos, V., Georgiou, S., and Tornari, V. (eds.) 2007. *Lasers in the preservation of cultural heritage*. New York: Taylor and Francis.

Fowles, P.S (2000) The Garden Temple at Ince Blundell: a case study in the recording and non-contact replication of decayed sculpture. *Journal of Cultural Heritage*, 1, S89–S91. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207400001904 [Accessed 28 January 2013].

Franceschi, E., Giorgi, M., Luciano, G., Palazzi, D. and Piccardi, E. (2004) Archaeometallurgical characterisation of two small copper-based statues from the Cividale Museum (Friuli, Italy). *Journal of Cultural Heritage*, 5 (2), 205–211. Available from: http://www.sciencedirect.com/science/article/pii/S1296207404000251 [Accessed 28 January 2013].

Freeth, T., Bitsakis, Y., Moussas, X., Seiradakis, J. H., Tselikas, A., Mangou, H., Zafeiropoulou, M., Hadland, R., Bate, D., Ramsey, A., Allen, M., Crawley, A., Hockley, P., Malzbender, T., Gelb, D., Ambrisco, W. and Edmunds, M. G. (2006) Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism. *Nature*, 444 (7119), 587–591. Available from:

http://www.nature.com/nature/journal/v444/n7119/full/nature05357.html [Accessed 28 January 2013].

Freitag, W. (2011) *Highlights from the Vienna Museum of clocks and watches*. Vienna: Wien Museum. Available from: http://issuu.com/wienmuseum/docs/wien_museum_uhrenmuseum_highlights_/18 [Accessed 28 January 2014].

Friedrich, K. M., Nemec, S., Czerny, C., Fischer, H., Plischke, S., Gahleitner, A., Viola, T. B., Imhof, H., Seidler, H. and Guillen, S. (2010) The story of 12 Chachapoyan mummies through multidetector computed tomography. *European Journal of Radiology*, 76 (2), 143–150. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19664893 [Accessed 28 January 2014].

Frischer, B. (2011) Art and Science in the Age of Digital Reproduction: From Mimetic Representation to Interactive Virtual Reality. *Virtual Archaeology Review*, 2 (4), 19-32. Available from: http://www.varjournal.es/doc/varj02_004_06.pdf [Accessed 28 January 2014].

Fukunaga, K., Hosako, I., Duling III, I. N. and Picollo, M. (2009) Terahertz imaging systems: a non-invasive technique for the analysis of paintings. IN: Pezzati, L. and Salimbeni, R. (eds.) *Proceedings of SPIE 7391. O3A: Optics for Arts, Architecture, and Archaeology II,* Munich, 17–18 June 2009. Bellingham: SPIE. Available from: http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=784448 [Accessed 16 November 2014].

Funkhouser, T., Min, P., Kazhdan, M., Chen, J., Halderman, A., Dobkin, D. and Jacobs, D. (2003) A search engine for 3D models. *ACM Transactions on Graphics*, 22 (1), 83–105. Available from: http://cvs.cs.umd.edu/~djacobs/pubs_files/tog03.pdf [Accessed 28 January 2014].

Gabellone, F. (2009) Ancient contexts and virtual reality: From reconstructive study to the construction of knowledge models. *Journal of Cultural Heritage*, 10 (Supplement 1), 112–117. Available from:

http://www.sciencedirect.com/science/article/pii/S129620740900140X [Accessed 28 January 2014].

Gabov, A. (2010). *IRR RTI using the Osiris.* Available from: http://rtiican.wordpress.com/2010/01/10/irr-rti-using-osiris/ [Accessed 28 January 2014].

Gabov, A. and Bevan, G. (2011) Recording the weathering of outdoor stone monuments using reflectance transformation imaging (RTI): the case of the Guild of All Arts (Scarborough, Ontario). *Journal of the Canadian Association for Conservation*, 36, 3–14. Available from: https://www.cac-accr.ca/files/pdf/Vol36_Doc1.pdf [Accessed 28 January 2014].

Gama Leitão, H. C. and Stolfi, J. (2002) A multiscale method for the reassembly of two-dimensional fragmented objects. *Pattern Analysis and Machine Intelligence, IEEE Transactions*, 24 (9), 1239– 1251. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=andarnumber=1033215 [Accessed 20 November 2014].

Gavrilov, D., Ibarra-Castanedo, C., Maeva, E., Grube, O., Maldague, X. and Maev, R. (2008) Infrared methods in noninvasive inspection of artwork. IN: Art 2008: Proceedings of the 9th International Conference on NDT of Art, Jerusalem, Israel, 25–30 May 2008. Available from: http://www.ndt.net/article/art2008/papers/040Gavrilov.pdf [Accessed 28 January 2014].

Geary, A. and Howe, E. (2009) Three dimensional documentation and virtual restoration of the Lichfield Angel. *Journal of the Institute of Conservation*, 32 (2), 165–179. Available from: http://www.tandfonline.com/doi/abs/10.1080/19455220903059875 [Accessed 28 January 2014].

Geary, A. and Sandy, M. (2004) A Haptic Training Simulation for Paper Conservation: Preliminary Results.IN: Buss M. and Fritschi M. (eds.) *Proceedings of the 4th International Conference EuroHaptics 2004*, Mu̇nchen, 5-7 June 2004. Mu̇nchen: Inst. of Automatic Control Engineering, 428–431. Available

from: http://www.eurohaptics.vision.ee.ethz.ch/2004/115f.pdf [Accessed 28 January 2014].

Geschke, R. (2004) Ceramic gap-fills for ceramic restoration. *The Conservator,* 28 (1), 74-83. Available from: http://www.tandfonline.com/doi/abs/10.1080/01410096.2004.9995206 [Accessed 28 January 2014].

Ghysels, M. (2014) *CT scan analysis of sculptures and works of art*. Available from: http://www.scantix.com/faq/does-a-ct-scan-affect-the-thermoluminescence-signal-tl/ [Accessed 16 November 2014].

Gilberg, M. (1987) Friedrich Rathgen: The Father of Modern Archaeological Conservation. *Journal of the American Institute for Conservation*, 26 (4), 105-120. Available from: http://cool.conservation-us.org/jaic/articles/jaic26-02-004_2.html [Accessed 28 January 2014].

Gilboa, A., Karasik, A., Sharon, I. and Smilansky, U. (2004) Towards computerized typology and classification of ceramics. *Journal of Archaeological Science*, 31 (6), 681-694. Available from: http://www.sciencedirect.com/science/article/pii/S0305440303001808 [Accessed 28 January 2014].

Ginell, W. (1994) The Nature of Changes Caused by Physical Factors. IN: Krumbein, W. E., Brimblecombe, P., Cosgrove, D. E. and Staniforth, S. (eds.) *Durability and change: the science, responsibility, and cost of sustaining cultural heritage*. Chichester: John Wiley, 81-94.

Giusti, A. (1999) Reversibility in the restoration of stone artefacts: Real possibilities and objective limits. IN: Oddy, W. and Carroll S. (eds.) *Reversibility: Does it exist?* London: British Museum, 91-98.

Goble, C., Bhagat, J., Aleksejevs, S., Cruickshank, D., Michaelides, D., Newman, D., Borkum, M., Bechhofer, S., Roos, M., Li, P. and De Roure, D. (2010) myExperiment: a repository and social network for the sharing of bioinformatics workflows. *Nucleic Acids Research*, 38, 677-682. Available from:

http://nar.oxfordjournals.org/content/38/suppl_2/W677.full.pdf+html [Accessed 28 January 2014].

Goffer, Z. (1979) *Archaeological chemistry: a sourcebook on the applications of chemistry to archaeology*. Hoboken: John Wiley and Sons Inc.

Goldberg, D., Malon, C., & Bern, M. (2002) A global approach to automatic solution of jigsaw puzzles. IN: *Proceedings of the eighteenth annual symposium on Computational geometry*, Barcelona, 5 -7 June 2002. New York: ACM, 82-87. Available from: http://doi.acm.org/10.1145/513400.513410 [Accessed 16 November 2014].

Goldman, L.W. (2007) Principles of CT and CT technology. *Journal of nuclear medicine technology*, 35 (3), 115–28. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17823453 [Accessed 28 January 2014].

Goltz, D.M. (2012) A Review of Instrumental Approaches for Studying Historical Inks. *Analytical Letters*, 45 (4), 314–329. Available from: http://www.tandfonline.com/doi/abs/10.1080/00032719.2011.644712 [Accessed 28 January 2014].

Goodbrown-Brown, D. (1998) Surface values: coins under the microscope. IN: Goodburn-Brown, D. and Jones, J. (eds.) *Look after the pennies: numismatics and conservation in the 1990s*. London: Archetype Publications, 19–23.

Gosden, C. and Marshall, Y. (1999) The Cultural Biography of Objects. *World Archaeology*, 31 (2), 169-178.

Goskar, T. and Earl, G. (2010) Polynomial texture mapping for archaeologists. *British Archaeology*, 111, 28–31.

Gostner, P., Pernter, P., Bonatti, G., Graefen, A. and Zink, A. R. (2011) New radiological insights into the life and death of the Tyrolean Iceman. *Journal of Archaeological Science*, 38 (12), 3425–3431. Available from: http://www.sciencedirect.com/science/article/pii/S0305440311002731 [Accessed 28 January 2014].

Grammenos, D.B. (2004) *The Archaeological Museum of Thessaloniki*. Athens: OLKOS

Grant, M. S. (2000) The Use Of Ultraviolet Induced Visible-Fluorescence In The Examination Of Museum Objects , Part II. *Conserve O Gram*, 1(9), 1-3. Available from: http://www.nps.gov/museum/publications/conserveogram/01-09.pdf [Accessed 28 January 2014].

Grattan, D.W. and Barclay, R.L. (2010). A study of gap-fillers for wooden objects. *Studies in Conservation*, 33(2), 71–86.

Gray, S., Ross, C., Hudson-Smith, A. , Terras, M., and Warwick, C. (2012) Enhancing Museum Narratives with the QRator Project: a Tasmanian devil, a Platypus and a Dead Man in a Box. IN: Proctor, N. and Cherry, R. (eds.) *Museums and the Web 2012*, CA, USA, 11-14 April 2012. Museums and the Web LLC

Green, R. J. (2001) Gnathia and Other Overpainted Wares of Italy and Sicily: A Survey. IN: Lévêque, P., Morel, J. and Geny, E. (eds.) *Céramiques hellénistiques et romaines*. Besançon: Presses universitaires franc-comtoises, 57-103.

Griswold, J. and Uricheck, S. (1998) Loss compensation methods for stone. *Journal of the American Institute for Conservation*, 37 (1), 89–11. Available from: http://cool.conservation-us.org/jaic/articles/jaic37-01-007.html [Accessed 28 January 2014].

Grussenmeyer, P., Landes, T., Voegtle, T. and Ringle, K. (2008) Comparison methods of terrestrial laser scanning, photogrammetry and tacheometry data for recording of cultural heritage buildings. IN: Chen J., Jıan J. and Hans-Gerd M., (eds.) *Proceedings of the XXIst ISPRS congress*, Beijing, 3–11 July 2008. ISPRS, 213–218. Available from:http://isprsserv.ifp.uni-stuttgart.de/proceedings/XXXVII/congress/5_pdf/38.pdf [Accessed 28 January 2014].

Guarnieri, A., Remondino, F. and Vettore, A. (2005) Digital photogrammetry and data fusion applied to cultural heritage 3d modeling. *Heritage*, 36 (5). Available from:

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.72.3963andamp;rep=rep1andamp;type=pdf [Accessed 28 January 2014].

Guidi, G., Beraldin, J.A. and Atzeni, C.(2004) High-accuracy 3-D modeling of cultural heritage: the digitizing of Donatello's "Maddalena". *IEEE transactions on image processing*, 13 (3), 370–80. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15376928 [Accessed 28 January 2014].

Gunawardane, P., Wang, O., Scher, S., Rickards, I., Davis, J., and Malzbender, T., (2009) Optimized image sampling for view and light interpolation. IN: Debattista, K., Perlingieri, C., Pitzalis, D. and Spina, S. *Proceedings of the 10th International conference on Virtual Reality, Archaeology and Cultural Heritage,* Malta, 22-25 September 2009. Aire-la-Ville: Eurographics Association, 93-100.

Halskov, K. and Dalsgaard, P. (2011) Using 3-D projection to bring a statue to life. *Interactions*, 18 (3), 60–65. Available from: http://portal.acm.org/citation.cfm?doid=1962438.1962452 [Accessed 28 January 2014].

Hamiel, J. S. and Yoshida, J. S. (2012) *Evaluation and Application of Polynomial Texture Mapping (PTM) in the area of Shoe/Tire Impression Evidence.* Washington: U.S. Department of Justice. Available from: https://www.ncjrs.gov/pdffiles1/nij/grants/240591.pdf [Accessed 28 January 2014].

Hamilakis, Y. (2014) Postcards from the field: Studying the Neolithic figurines from Koutroulou Magoula [video, online*]. Corporeal engagements with clay*. Available from: http://vimeo.com/103500769 [Accessed 28 January 2014].

Hammer, Ø., Bengtson, S., Malzbender, T., and Gelb, D., 2002. Imaging fossils using reflectance transformation and interactive manipulation of virtual light sources. *Paleontologia Electronica*, 5 (4), 1-9. Available from: http://www.hpl.hp.com/research/ptm/papers/PaleoPaper.pdf [Accessed 28 January 2014].

Hanisch, F., Eberhardt, B. and Nill, B.(2000) Reconstruction and virtual model of the Schickard calculator. *Journal of Cultural Heritage*, 1(4), 335–340. Available

from: http://www.sciencedirect.com/science/article/pii/S1296207400010906 [Accessed 28 January 2014].

Hanke, K., Moser, M., Grimm-Pitzinger, A., Goldenberg, G., and Toechterle, U., (2008) Enhanced potential for archaeological finds based on 3D modeling. IN: Chen J., Jıan J. and Hans-Gerd M. (eds.) *Proceedings of the XXIst ISPRS congress*, Beijing, 3-11 July 2008. ISPRS, 3-8. Available from: http://www.isprs.org/proceedings/XXXVII/congress/5_pdf/34.pdf [Accessed 28 January 2014].

Happa, J., Williams, M., Turley, G., Earl, G., Dubla, P., Beale, G., Gibbons, G. and Debattista, K., Chalmers, A. (2009) Virtual relighting of a roman statue head from herculaneum: a case study. IN: Spencer, S.N. (ed.) *The 6th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa (AFRIGRAPH '09)*, Pretoria, 4-6, February 2009. New York: ACM, 5-12. Available from: http://doi.acm.org/10.1145/1503454.1503456 [Accessed 28 January 2014].

Hein, A. and Kilikoglou, V. (2015) Breaking pots – simulating design failures of transport amphorae by using the finite element method (FEM). IN: Papadopoulos, C., Paliou E., Chrysanthi, A., Kotoula, E. and Sarris, A. (eds.) *Proceedings of the 1st Conference on Computer Applications and Quantitative Methods in Archaeology Greek Chapter (CAA-GR) Archaeological Research in the Digital Age,* Rethymno, Crete, 6-8 March 2014. Rethymno: Institute for Mediterranean Studies – Foundation of Research and Technology (IMS-FORTH), 184-187. Available from: http://caa-gr.org/2014/CAA-GR_2014_Procs.pdf [Accessed 25 January 2015]

Heinz, G. (2002) Pharaoh Pepi I.: Documentation Of The Oldest Known Life-Size Metal Sculpture Using Laser Scanning And Photogrammetry. IN: Boehler, W. (ed.) *Proc. of the CIPA WG6 Int. Workshop on scanning for cultural heritage recording*, Corfu, September 2002. Thessaloniki: Ziti, 127-131. Available from: https://143.93.114.105/sites/default/files/public/data/p23_Heinz.pdf [Accessed 28 January 2014].

Hemmleb, M., Weritz, F., Schiemenz, A., Grote, A. and Maierhofer, C. (2006) Multi-spectral data acquisition and processing techniques for damage

detection on building surfaces. IN: Maas, H. G. and Schneider, D. (eds.) *Proceedings of the ISPRS Commission V Symposium 'Image Engineering and Vision Metrology'*, Dresden, 25-27 September 2006. Available from: http://www.isprs.org/proceedings/XXXVI/part5/paper/1260_Dresden06.pdf [Accessed 28 January 2014].

Henning, M. (2008) New media. IN: Macdonald, S. (ed.) *Companion to Museum Studies*. Chichester, Malden, MA: Blackwell Pub., 302–318.

Heslop, H., Davis, S., and Wilson, A. (2002) *An approach to the preservation of digital records*. Canberra: National Archives of Australia. Available from: http://www.aa.gov.au/Images/An-approach-Green-Paper_tcm16-47161.pdf [Accessed 28 January 2014].

Hespanha, J., Mclaughlin, M. and Sukhatme, G. (2001) Haptic collaboration over the internet. IN: Reinig, K. (ed.) *Support for Conference Entitled The Fifth PHANTOM Users Group Workshop*, Aspen, October 2000. Ft. Belvoir: Defence Technical Information Center, 1–5. Available from: http://www.andrew.cmu.edu/user/rgarg/research/Rajiv_PUG2000.pdf [Accessed 28 January 2014].

Hess, M. and Robson, S. (2010) 3D colour imaging for cultural heritage artefacts. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38 (5), 288–292.

Hewlett Packard (2005) *Making PTMs*. Available from: http://www.hpl.hp.com/research/ptm/MakingPtmNew.htm [Accessed 28 January 2014].

Hodges, H. (1976) *Artifacts: an introduction to early materials and technology*. London: John Baker.

Hoenige, C. (1991) The Identification of Blue Pigments in Early Sienese Paintings by Color Infrared Photography. *Journal of the American Institute for Conservation*, 30 (2), 115–124. Available from: http://www.jstor.org/stable/3179525 [Accessed 28 January 2014].

Hood, S. (1994) *The arts in prehistoric Greece*, 2nd edition. New York: Yale University Press.

Horie, V. (2011) *Materials for conservation*. 2nd edition. London: Routledge.

Horn, F. and Monreal, M. (2012) The head of the terracotta warrior with "green face": from 3D scanning to a colored replica using rapid prototyping. *Restauro: Forum für Restauratoren, Konservatoren und Denkmalpfleger*, 118 (5), 18-25

Hoskins, S. (2012) Towards a new ceramic future. *Ceramic Review*, 255, 64-65.

Hoskins, S. and Huson, D. (2013) *Can Egyptian Paste Techniques (Faience) Be Used For 3D Printed, Solid Free-form Fabrication of Ceramics?* Available from: http://www.uwe.ac.uk/sca/research/cfpr/research/3D/research_projects/Egyptian_Paste.html [Accessed 28 January 2014].

Huang, P., Deng, D. and Chen, Y. (2013) Modeling and Fabrication of Heterogeneous Three-dimensional Objects based on Additive Manufacturing. IN: *2013 Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exhibition (IMECE2013)-Volume 2 Parts A & B: Advanced Manufacturing*, San Diego, 15-21 November 2013. New York: American Society of Mechanical Engineers, 215–230. Available from: http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/2013/2013-17-Huang.pdf [Accessed 28 January 2014].

Huang, Q. X., Flöry, S., Gelfand, N., Hofer, M. and Pottmann, H. (2006) Reassembling Fractured Objects by Geometric Matching. *ACM Transactions on Graphics (TOG)*, 25 (3), 569–578. Available from: http://dl.acm.org/citation.cfm?id=1141925 [Accessed 28 January 2014].

Huber, E. Iaccarino Idelson, A. and Serino, C. (2009) The mechanical assembly of a renaissance teracotta relief: restoring a tin glazed work of art. IN: Ambers, J., Higgit, C., Harrison, L. and Saunders, D. (eds.) *Holding it all together: Ancient and Modern Approaches to Joining, Repair and Consolidation*, London, 21-22 February 2008. London: Archetype, 199-204.

Hughes, S. (2011) CT Scanning in Archaeology. IN: Saba, L. (ed.) *Computed Tomography - Special Applications*. InTech, Ch 4. Available from:

http://www.intechopen.com/books/computed-tomography-special-applications/ct-scanning-in-archaeology [Accessed 28 January 2014].

Hunter, J. and Gerber, A. (2010) Harvesting community annotations on 3D models of museum artefacts to enhance knowledge, discovery and re-use. *Journal of Cultural Heritage*, 11 (1), 81–90. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207409001083 [Accessed 28 January 2014].

ICOM: CIDOC-CRM (2014) *The CIDOC Conceptual Reference Model*. Available from: http://www.cidoc-crm.org/official_release_cidoc.html [Accessed 28 January 2014].

ICOM-CC (2010) *The Conservator-Restorer:a Definition of the Profession*. Available from: http://www.icom-cc.org/47/about-icom-cc/definition-of-profession/ [Accessed 28 January 2014].

Ignatiadou, D. (2009) Pre-Roman glassworking. Nine misconceptions. In Gatzolis, C. (ed.) *Conservation Day 2009, GLASS*. Thessaloniki: AMTH, 69–84.

Imaterialise (2013) *The periodic table of materials*. Available from: http://i.materialise.com/materials [Accessed 28 January 2014].

Institute of Industrial Engineers (2012) It's right at the museum: Jefferson statue for the Smithsonian shows power of additive manufacturing. *Industrial Engineer*, 44 (5). Available from: http://www.iienet2.org/IEMagazine/Details.aspx?id=30730 [Accessed 28 January 2014].

Ioannides, M. and Wehr, A. (2002) 3D-reconstruction and re-production in archaeology. IN: Boehler, W. (ed.) *Proc. of the CIPA WG6 Int. Workshop on scanning for cultural heritage recording*, Corfu, September 2002. Thessaloniki: Ziti. Available from: http://www.nav.uni-stuttgart.de/navigation/publikationen/fachartikel/2002/wehr_korfu.pdf [Accessed 28 January 2014].

Ioannidis, C. and Tsakiri, M. (2003) Laser scanning and photogrammetry for the documentation of a large statue - experiences in the combined use. IN:

Altan, M. (ed.) *New Perspectives to save Cultural Heritage. Proceedings of the XIXth International Symposium, CIPA 2003*, Antalya, 30 September - 4 October 2003. Istanbul, Turkey: CIPA. Available from: http://cipa.icomos.org/fileadmin/template/doc/antalya/137.pdf [Accessed 28 January 2014].

Isenberg, T., Neumann, P., Carpendale, S., Sousa, M. C. and Jorge, J. A. (2006) Non-Photorealistic Rendering in Context : An Observational Study. IN: DeCarlo D. and Markosian, L. (eds.) *Proceedings of the 4th international symposium on Non-photorealistic animation and rendering (NPAR 2006)*, Annecy, 05 - 07 June 2006. New York: ACM, 115–126.

Ishii, M., Moriyama, T., Toda, M., Kohmoto, K. and Saito, M. (2008) Color degradation of textiles with natural dyes and of blue scale standards exposed to white LED lamps: Evaluation of white LED lamps for effectiveness as museum lighting. *Journal of Light & Visual Environment*, 32 (4), 370-378.

ISTI-CNR (2014a). *MeshLab Documentation*, Available from: http://www.cyi.ac.cy/system/files/MeshLab%20Documentation1.pdf [Accessed 28 January 2014].

ISTI-CNR (2014b) *MeshLab v1.3.3* [computer program]. Available from: http://meshlab.sourceforge.net [Accessed 28 January 2014].

ISTI-CNR/3DCOFORM (2014) *Fragment Reassembler v1.0* [computer program]. Available from: http://vcg.isti.cnr.it/~pietroni/reassebly/index.html [Accessed 28 January 2014].

Jackson, J. B., Labaune, J., Bailleul-Lesuer, R., D'Alessandro, L., Whyte, A., Bowen, J. W., ... and Mourou, G. (2014) Terahertz pulse imaging in archaeology. *Frontiers of Optoelectronics*, 1-12. Available from: http://link.springer.com/article/10.1007/s12200-014-0446-y [Accessed 16 November 2014].

Jacobs, P.F. and Tsioukas, V. (2004) Toward a Digital Collection: The Lois Dowdle Cobb Museum. *Museology*, 1, 44–50. Available from:

http://museology.ct.aegean.gr/articles/200711111326.pdf [Accessed 19 March 2014].

Jansen, R. J., Koens, H. F., Neeft, C. W. and Stoker, J. (2001) Scenes from the past: CT in the archaeologic study of ancient Greek ceramics. *Radiographics*, 21 (2), 315–21. Available from: http://pubs.rsna.org/doi/full/10.1148/radiographics.21.2.g01mr12315 [Accessed 19 March 2014].

Jansen, R. J., Poulus, M., Kottman, J., de Groot, T., Huisman, D. J. and Stoker, J. (2006) CT: A New Nondestructive Method for Visualizing and Characterizing Ancient Roman Glass Fragments in Situ in Blocks of Soil. *Radiographics*, 26 (6), 1837–1844. Available from: http://pubs.rsna.org/doi/abs/10.1148/rg.266065079 [Accessed 19 March 2014].

Janssens, K., Dik, J., Cotte, M. and Susini, J. (2010) Photon-based techniques for nondestructive subsurface analysis of painted cultural heritage artifacts. *Accounts of chemical research*, 43 (6), 814–25. Available from: http://www.ncbi.nlm.nih.gov/pubmed/20462197 [Accessed 19 March 2014].

Jewell, O. M., Constanze, E., Frankland, T., Earl, G. and Moreau, L. (2012) The Xeros Data Model: Tracking Interpretations of Archaeological Finds. IN: Groth, P. and Frew, J. (eds) *Provenance and annotation of data and processes*. Berlin: Springer, 139-151.

Jones, A. (2002) *Archaeological Theory and Scientific Practice*. Cambridge: Cambridge University Press.

Jones, N. (2012) Science in three dimensions: The print revolution. Three dimensional printers are opening up new worlds to research. *Nature*, 487, 22–23. Available from: http://www.nature.com/news/science-in-three-dimensions-the-print-revolution-1.10939 [Accessed 19 March 2014].

Jovanovic, J. (2010) Roman bronze vessels from the Archaeological Museum in Split. *Journal of Dalmatian archaeology and history*, 1 (103), 191–232. Available from:

http://hrcak.srce.hr/index.php?show=clanakandid_clanak_jezik=93253andlang=en [Accessed 19 March 2014].

Kadobayashi, R., Kochi, N., Otani, H. and Furukawa, R. (2004) Comparison and evaluation of laser scanning and photogrammetry and their combined use for digital recording of cultural heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 35 (5), 401-406. Available from: http://www.isprs.org/proceedings/XXXV/congress/comm5/papers/586.pdf [Accessed 19 March 2014].

Kamal, O. S., Ware, G. A., Houston, S., Chabries, D. M., Christiansen, R. W., Brady, J. and Graham, I. (1999) Multispectral Image Processing For Detail Reconstruction and Enhancement of Maya Murals from La Pasadita, Guatemala. *Journal of Archaeological Science*, 26 (11), 1391–1407. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440399904156 [Accessed 19 March 2014].

Kampel, M. and Sablatnig, R. (2003) Profile-based Pottery Reconstruction. IN: Dyer, C. and Perona, P. (eds.) *2003 Conference on Computer Vision and Pattern Recognition Workshop*, Madison, 16-22 June 2003. Los Alamitos: IEEE Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4624518 [Accessed 16 January 2013].

Kampel, M. and Sablatnig, R. (2004) 3D puzzling of archeological fragments. IN: Bostjan, L. (ed.) *Proc. of 9th Computer Vision Winter Workshop*, Piran, 4-6 February 2004, Bled: Slovenian Pattern Recognition Society, 31-40.

Kamrani, A.K. and Nasr, E.A. (2005) *Rapid Prototyping: Theory and Practice*. New York: Springer

Kapetanakis, P. (2010) *Brooklyn Museum: IR and UV Examination of Egyptian Papyrus*. Available from: http://www.brooklynmuseum.org/community/blogosphere/2010/12/03/ir-and-uv-examination-of-egyptian-papyrus/ [Accessed 16 January 2013].

Kariya, H. (1997) Suitable fill materials for ceramics used at Kaman-Kalehöyük. *Anatolian archaeological studies*, VI (6), 309–318.

Karl, S., Mara, H. and Krömker, S. (2014). *Insights into manufacturing techniques of archaeological pottery*. Heidelberg: Universitätsbibliothek Heidelberg.

Karlik, S. J., Bartha, R., Kennedy, K. and Chhem, R. (2007) MRI and Multinuclear MR Spectroscopy of 3,200-Year-Old Egyptian Mummy Brain. *American Journal of Roentgenology*, 189 (2), 105–110. Available from: http://dx.doi.org/10.2214/AJR.07.2087 [Accessed March 19, 2014].

Karsten, A. and Earl, G. (2010) *HMS Stirling Castle, Kent. The Stirling Castle wood recording project. English Heritage Research Reports, (65-2010).* Portsmouth: English Heritage. Available from: http://services.english-heritage.org.uk/ResearchReportsPdfs/065_2010WEB.pdf [Accessed March 19, 2014].

Kawase, K., Shibuya, T., Hayashi, S. and Suizu, K. (2010) THz imaging techniques for nondestructive inspections. *Comptes Rendus Physique*, 11 (7-8), 510-518.

Keck, S. (1996) Further material for a history of conservation. IN: Stanley-Price, N., Talley, M. K. and Vaccaro, A. M. (eds.) *Historical and philosophical issues in the conservation of cultural heritage.* Los Angeles: Getty Conservation Institute, 281–287.

Kemp, J. (2009) Practical Ethics v2.0. IN: Richmond A. and Bracker, A. (eds.) *Conservation: Principles, Dilemmas, and Uncomfortable Truths.* Oxford: Butterworth-Heinemann, 60–72.

Kerr, É. (2008) Renaissance painted cassoni. *Conservation Journal*, 56. Available from: http://www.vam.ac.uk/content/journals/conservation-journal/issue-56/renaissance-painted-cassoni/ [Accessed 28 January 2013].

Kite, M. and Thomson, R. (eds) (2006) *Conservation of Leather and related materials*, Oxford: Elsevier Butterworth-Heinemann.

Kleber, F. and Sablatnig, R. (2009) A Survey of Techniques for Document and Archaeology Artefact Reconstruction. IN: *10th International Conference on Document Analysis and Recognition*, Barcelona, 26-29 July 2009. Los Alamitos: IEEE, 1061–1065. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5277502 [Accessed 28 January 2013].

Klein, R. and Schwartz, C. (2010) *3D-COFORM. D.4.2 – Second Year Report, WP4 – 3D Artefact Acquisition, Version 1.4.*, Available from: http://www.3dcoform.eu/downloads/Period_2/3DC_D_4_2_WP4_YR2_FINAL.pdf [Accessed 28 January 2013].

Knox, K., Johnston, R. and Easton, R.L.J. (1997) Imaging the Dead Sea Scrolls. *Optics and Photonics News*, 8 (8), 30–34. Available from: http://dx.doi.org/10.1364/OPN.8.8.000030 [Accessed 16 January 2013].

Koob, S. (1998) Obsolete fill materials found on ceramics. *Journal of the American Institute for Conservation*, 37 (1), 49–67. Available from: http://cool.conservation-us.org/jaic/articles/jaic37-01-005.html [Accessed 16 January 2013].

Kotitsa, Z. (2012) Metal-coated Pottery from Macedonia in the Late Classical and Hellenistic period. IN: Drougou, S. and Touratsoglou, G. (eds.) Topics on Hellenistic pottery in ancient Macedonia. Athens: Archaeological Receipts Fund.

Kotoula, E. (2011) Old interventions and new possibilities: Applications of digital technology in re-conservation. *e-conservation magazine*, 19, 40–47. Available from: http://www.e-conservationline.com/content/view/997 [Accessed 16 January 2013].

Kotoula, E. (2013a) Microscopic RTI of gilded silver discs from the Derveni tombs, Macedonia, Greece. IN: Duffy, S. (ed.) *Multi-light Imaging for Heritage Applications. English Heritage*, 21–23. Available from: http://www.english-heritage.org.uk/publications/multi-light-imaging-heritage-applications/ [Accessed 16 January 2014].

Kotoula, E. (2013b) Application of RTI in Museum Conservation. IN: Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. and Wheatley, D. (eds.) *Archaeology in the Digital Era. Volume II. E-Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA)*, Southampton, 26-29 March 2012. Amsterdam: Amsterdam University Press, 232-240.

Kotoula, E. and Earl, G. (2011) RTI in conservation examination, analysis and documentation. Poster presented at Computer Applications and Quantitative Methods in Archaeology-UK Chapter, Birmingham, 1-2 April 2011. Available from: https://www.academia.edu/7079090/RTI_in_conservation_examination_analysis_and_documentation [Accessed 15 April 2011].

Kottke, J. and Hinchman, J. (2009) *An Investigation of Quantifying and Monitoring Stone Surface Deterioration Using Three Dimensional Laser Scanning*, Master of Science Thesis, University of Pennsylvania. Available from: http://repository.upenn.edu/hp_theses/128 [Accessed 16 January 2013].

Kraskovská, L. (1978) *Roman bronze vessels from Slovakia*. Oxford: British Archaeological Reports.

Kruth, J. P., Wang, X., Laoui, T. and Froyen, L. (2003) Lasers and materials in selective laser sintering. *Assembly Automation*, 23 (4), 357–371. Available from: http://www.emeraldinsight.com/10.1108/01445150310698652 [Accessed 16 April 2013].

Kucukkaya, A.G. (2004) Photogrammetry and remote sensing in archaeology. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 88 (1-3), 83–88. Available from: http://linkinghub.elsevier.com/retrieve/pii/S002240730400130X [Accessed 8 November 2012].

Kumar, S., Snyder, D., Duncan, D., Cohen, J. and Cooper, J. (2003) Digital preservation of ancient cuneiform tablets using 3D-scanning. IN: *Proceedings of Fourth International Conference on 3-D Digital Imaging and Modeling, 3DIM 2003*, Alberta, 6-10 October 2003. Los Alamitos: IEEE, 326–333. Available

from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1240266 [Accessed 8 November 2012].

Kushel, D. (2002) From the Electronic Media Group: Digital Documentation: We Are There, but Enter with Care. *AIC News*, 27 (6). Available from: http://cool.conservation-us.org/coolaic/sg/emg/library/pdf/kushel/kushel-we-are-there.pdf [Accessed 8 November 2012].

Kushel, D.A. (1985) Applications of transmitted infrared radiation to the examination of artifacts. *Studies in conservation*, 30 (1), 1–10.

Kuzminsky, S.C. and Gardiner, M.S. (2012) Three-dimensional laser scanning: potential uses for museum conservation and scientific research. *Journal of Archaeological Science*, 39 (8), 2744–2751. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440312001409 [Accessed 12 December 2013].

Lagerqvist, B. (1999) A system approach to conservation and resources management. Photogrammetry as a base for desighning documentation models. IN: *Mapping and Preservation for the New Millenium*, Olinda, 3-6 October 1999. Brazil: Society of Cartography, Geodesy, Photogrammetry, and Remote Sensing.

Lahlil, S. and Martin, E. (2012) Characterisation of 18 Melkite icons dating from the 17th to the 19th c. AD. *Journal of Cultural Heritage*, 13 (3), 332–338. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207411001166 [Accessed 16 January 2013].

Lambers, K., Eisenbeiss, H., Sauerbier, M., Kupferschmidt, D., Gaisecker, T., Sotoodeh, S. and Hanusch, T. (2007) Combining photogrammetry and laser scanning for the recording and modelling of the Late Intermediate Period site of Pinchango Alto, Palpa, Peru. *Journal of Archaeological Science*, 34 (10), 1702–1712. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440306002731 [Accessed 8 November 2012].

Lane, H. (1974) The restoration of thin metal vessels using a glass-fiblre and polyester resin. *Studies in Conservation*, 19 (4), 227–232.

Lang, J. and Middleton, A. (1997). *Radiography of cultural material*. Oxford: Butterworth/Heinemann.

Lanitis, A., Stylianou, G. and Voutounos, C., 2012. Virtual restoration of faces appearing in byzantine icons. *Journal of Cultural Heritage*, 13 (4), 404–412. Available from: http://www.sciencedirect.com/science/article/pii/S1296207412000027 [Accessed January 18, 2013].

Larkin, N.R. (2010) Literally a "mammoth task": The conservation, preparation and curation of the West Runton Mammoth skeleton. *Quaternary International*, 228 (1-2), 233–240. Available from: http://linkinghub.elsevier.com/retrieve/pii/S104061821000265X [Accessed 18 January 2013].

Lavédrine, B. (2009) *Photographs of the past*. Los Angeles: Getty Conservation

Lee, Y. (2009) *Principles of terahertz science and technology*. New York: Springer.

Lehmann, E. H. (2006) Scientific Reviews: Using Neutron Imaging Methods for Non-Invasive Investigation of Museum Objects. *Neutron News*, 17 (1), 22-29. Available from: http://www.tandfonline.com/doi/pdf/10.1080/10448630500517 62 [Accessed 18 January 2014].

Lehmann, E.H., Deschler-Erb, E. and Ford, A. (2010) Neutron tomography as a valuable tool for the non-destructive analysis of historical bronze sculptures. *Archaeometry*, 52 (2), 272–285. Available from: http://dx.doi.org/10.1111/j.1475-4754.2009.00480.x [Accessed 18 January 2014].

Lehoux, D. (2013) Ancient Science in a Digital Age. *Isis*, 104 (1), 111–118. Available from: http://www.jstor.org/stable/10.1086/669892 [Accessed 18 January 2014].

Levoy, M., Pulli, K., Curless, B., Rusinkiewicz, S., Koller, D., Pereira, L., Ginzton, M., Anderson, S., Davis, J., Ginsberg, J., Shade, J. and Fulk, D. (2000) The Digital Michelangelo Project: 3D scanning of large statues. IN: Brown, J.S. and Akeley, K. (eds.) *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, New Orleans, 23 - 28 July 2000. New York: ACM Press/Addison-Wesley Publishing Co., 131–144. Available from: http://dx.doi.org/10.1145/344779.344849 [Accessed 26 October 2012].

Levy, R. and Dawson, P. (2009) Using finite element methods to analyze ancient architecture: an example from the North American Arctic. *Journal of Archaeological Science* 36 (10): 2298–2307. Available from: http://people.ucalgary.ca/~rmlevy/Publications/YJASC2181.pdf [Accessed 5 October 2014]

Liang, H. (2011) Advances in multispectral and hyperspectral imaging for archaeology and art conservation. *Applied Physics A*, 106 (2), 309–323. Available from: http://www.springerlink.com/index/10.1007/s00339-011-6689-1 [Accessed 26 October 2012].

Lin, Y. and Seales, W.B. (2005) Opaque document imaging: building images of inaccessible texts. IN: *Tenth IEEE International Conference on Computer Vision (ICCV'05)*, *Volume 1*, Beijing, 17-21 October 2005. Los Alamitos: IEEE, 662–669 Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1541317 [Accessed 26 October 2012].

Lipson, H. and Kurman, M. (2013) *Fabricated: The New World of 3D Printing*. Indianapolis: John Wiley and Sons

Logan, J.A., Barclay, R. L., Bloskie, P., Newton, C. and Selwyn, L. (2010) Saving the Ferryland Cross: 3D Scanning, Replication, and Anoxic Storage. IN: Williams, E. and Peachey, C. (eds.) *The Conservation of Archaeological Materials: Current Trends and Future Directions. BAR International Series 2116*. Oxford: Archaeopress, 127-134.

Lyon, C. (2004*) Viewing Polynomial Texture Maps Using Java, Harvard Extension School.* Available from: http://materialobjects.com/ptm/overview.pdf [Accessed 26 October 2012].

Macchia, A., Cesaro, S. N., Campanella, L., Maras, A., Rocchia, M. and Roscioli, G. (2013) Which Light for Cultural Heritage: Comparison of Light Sources with Respect to Realgar Photodegradation. *Journal of Applied Spectroscopy*, 80 (5), 637-643.

Macdonald, L. W. (2011) Visualising an Egyptian Artefact in 3D: Comparing RTI with Laser Scanning. IN: Dunn, S., Bowen, J. and Ng, K. (eds.) *EVA London 2011. Proceedings of the 2011 international conference on Electronic Visualisation and the Arts,* London, 6 - 8 July 2011. Swindon: British Computer Society (BCS). Available from: http://ewic.bcs.org/upload/pdf/ewic_ev11_s8paper4.pdf [Accessed 26 October 2012].

Maino, G. (2007) Digitization and Multispectral Analysis of Historical Books and Archival Documents: Two Exemplary Cases. IN: *14th International Conference of Image Analysis and Processing - Workshops (ICIAP 2007),* Modena, 10-14 September 2007. Los Alamitos: IEEE, 119–124. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4427487 [Accessed 26 October 2012].

Maino, G. (2009) Paintings' investigation by means of tomographic and multispectral imaging. IN: *DGaO Proceedings 2009*. Available from: http://www.dgao-proceedings.de/download/110/110_a30.pdf [Accessed 10 March 2015].

Malkogeorgou, T. (2011) Folding, stitching, turning: putting conservation into perspective. *Journal of Material Culture*, 16 (4), 441–455. Available from: http://mcu.sagepub.com/cgi/doi/10.1177/1359183511424829 [Accessed 26 October 2012].

Malzbender, T. and Ordentlich, E. (2005). *Maximum entropy lighting for physical objects*. Hewlett-Packard Technical Report HPL-2005-68. Available from: http://www.hpl.hp.com/techreports/2005/HPL-2005-68.html [Accessed 10 June 2013].

Malzbender, T., Gelb, D. and Wolters, H. (2001) Polynomial texture maps. IN: Pocock, L. (ed.) *Proceedings of the 28th annual conference on Computer*

graphics and interactive techniques, Los Angeles, 12-17 August 2001. New York: ACM, 519–528. Available from: http://doi.acm.org/10.1145/383259.383320 [Accessed 26 October 2012].

Malzbender, T., Gelb, D., Wolters, H. and Zuckerman, B. (2004) Enhancement of Shape Perception by Surface Reflectance Transformation. IN: Girod, B. Magnor, M., Seidel, H.P. (eds.) *Vision, Modelling and Visulization 2004*, Stanford, 16-18 November 2004. Berlin: Akademishe Verlagsgesellsaft Aka GmbH, 183–186.

Malzbender, T., Wilburn, B., Gelb, D. and Ambrisco, B. (2006) Surface enhancement using real-time photometric stereo and reflectance transformation. IN: Akenine-Möller, T. and Heidrich, W. (eds.) *Proceedings of the 17th Eurographics conference on Rendering Techniques (EGSR'06)*, Nicosia, 26 – 28 June, 2006. Aire-la-Ville: Eurographics Association, 245–250. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.72.1703andamp;rep=rep1andamp;type=pdf [Accessed 26 October 2012].

Marchelli, G., Prabhakar, R., Storti, D. and Ganter, M. (2011) The guide to glass 3D printing: Developments, methods, diagnostics and results. *Rapid Prototyping Journal*, 17 (3), 187–194. Available from: http://www.emeraldinsight.com/doi/full/10.1108/13552541111124761 [Accessed 26 October 2012].

Marie, I. and Qasrawi, H. (2005) Virtual assembly of pottery fragments using moiré surface profile measurements. *Journal of Archaeological Science*, 32 (10), 1527–1533. Available from: http://www.sciencedirect.com/science/article/pii/S0305440305000944 [Accessed 17 January 2014].

Marsh, G.S. (1978) The use of ultraviolet radiation in the examination of works of art, artefacts and informational resources. *Australian Institute for the Conservation of Cultural Material Bulletin*, 4(2-3), 29–40.

Martinez, K., Cupitt, J., Saunders, D., and Pillay, R. (2002) Ten years of art imaging research. *Proceedings of the IEEE*, 90 (1), 28–41. Available from:

http://eprints.soton.ac.uk/256271/1/procieee2002.pdf [Accessed 17 January 2014].

Mechelke, K., Kersten, T.P. and Lindstaedt, M. (2007) Comparative investigations into the accuracy behaviour of the new generation of terrestrial laser scanning systems. IN: Grün, A. and Kahmen, H. (eds.) *Optical 3-D Measurement Techniques VIII*, Zurich, 9-12 July 2007. Heidelberg: ETH, 319-327. Available from: http://dev.cyark.org/temp/hcuhamburgmechelkeetal2007.pdf [Accessed 29 November 2012].

Mees, F., Cornelis, E., Jacobs, P., Cárbo, M. T. D. and Römich, H. (2009) Microfocus X-ray computed tomography analysis of corroded glass objects. *Engineering Geology*, 103 (3-4), 93–99. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0013795208001737 [Accessed 29 November 2012].

Melillo, L. (2013) The Ephebe from the Vial dell'Abbondanza. History of a restoration. IN: Risser, E. Saunders, D. (eds) *The restoration of ancient bronzes*. Los Angeles, California: Getty Publications, 57-63.

Menci Software, 2013. *SUMUS-2011*. Available from: http://www.menci.com/special-apps/12-special-apps/60-sumus-2011 [Accessed 21 January 2013].

Messier, P. (2014) *Monkey Brain Project Page*. Available from: http://paulmessier.com/pm/mb.html [Accessed 14 November 2014].

Michael, G. (2001) X-ray computed tomography. *Physics Education*, 36 (6), 442–451.

Microsoft (2014) *Photosynth.* Available from: http://photosynth.net/ [Accessed 20 January 2014].

Miles, G. (2011) Object Handling. IN: Caple, C. (ed.) *Preventive Conservation in Museums*. London: Routledge, 57–62.

Miles, J., Earl, G., Hinton, D., Sinclair, I. and Mavrogordato, M. (2012) The use of computed tomography within the study of archaeological coins. Paper presented at Computer Applications and Quantitative Methods in Archaeology-CAA 2012, Southampton, 26-29 March.

Milojevic, D., Laugerotte, C., Dunham, P., and Warzée, N. (2005) Computers and 3D Image Synthesis as Tools for Archaeology. IN: Milić, L. (ed.) *EUROCON 2005 - The International Conference on Computer as a Tool.Vol 2,* Belgrade, Serbia and Montenegro, 21-24 November 2005, Piscataway NJ: IEEE, 1036-1037. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1630126 [Accessed 16 January 2013].

Modlinger, M. (2011) Bronge Age Weapons: examples of 3D Computed Tomography in archaeology. Paper presented at Imaging in Conservation: Looking at artefacts under new light. ICON Archaeology and Science Group, STFC Rutherford Appleton Laboratory, Harwell Campus, Oxfordshire, 10-11 November 2011.

Molitch-Hou, M. (2014) Now You Can 3D Print with Memory Foam. Available from: http://3dprintingindustry.com/ [Accessed 20 January 2015]

Molitch-Hou, M. (2014) PolyMakr Offers 3 New 3D Printing Materials on Kickstarter. Available from: http://3dprintingindustry.com [Accessed 20 January 2015]

Montani, I., Sapin, E., Pahud, A. and Margot, P. (2012) Enhancement of writings on a damaged medieval manuscript using ultraviolet imaging. *Journal of Cultural Heritage*, 13 (2), 226-228. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207411000884 [Accessed 16 January 2013].

Moon, T., Schilling, M.R. and Thirkettle, S. (1992) A note on the use of false-color infrared photography in conservation. *Studies in conservation*, 37 (1), 42-52.

Moreau, L., Clifford, B., Freire, J., Futrelle, J., Gil, Y., Groth, P., Kwasnikowska, N., Miles, S., Missier, P., Myers J., Plale, B., Simmhan, Y., Stephan, E. and den Bussche, J. V. (2011) The open provenance model core specification (v1.1). *Future Generation Computer Systems*, 27 (6), 743–756. Available from: http://www.sciencedirect.com/science/article/pii/S0167739X10001275 [Accessed 16 January 2013].

Morigi, M. P., Casali, F., Bettuzzi, M., Bianconi, D., Brancaccio, R., Cornacchia, S., Pasini, A., Rossi, A., Aldrovandi, A., and Cauzzi, D. (2007) CT investigation of two paintings on wood tables by Gentile da Fabriano. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 580 (1), 735–738. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0168900207010030 [Accessed 18 January 2013].

Morigi, M. P., Casali, F., Bettuzzi, M., Brancaccio, R. and d'Errico, V. (2010) Application of X-ray Computed Tomography to Cultural Heritage diagnostics. *Applied Physics A,* 100 (3), 653–661. Available from: http://www.springerlink.com/index/10.1007/s00339-010-5648-6 [Accessed 15 January 2013].

Moutsatsou, A., Skapoula, D. and Doulgeridis, M. (2011) The Contribution of Transmitted Infrared Imaging to Non-Invasive Study of Canvas Paintings at the National Gallery – Alexandros Soutzos Museum, Greece. *e-conservation magazine,* 22, 53–61. Available from: http://www.e-conservationline.com/content/view/1038 [Accessed January 18, 2013].

Mudge, M., Ashley, M. and Schroer, C. (2007) A digital future for cultural heritage. IN: Georgopoulos, A. (ed.) *Proceedings of the XXI International Symposium CIPA 2007*, Athens, 1-6 October 2007, Athens: CIPA. Available from: http://cipa.icomos.org/fileadmin/template/doc/ATHENS/FP104.pdf [Accessed 26 May 2014].

Mudge, M., Malzbender, T., Chalmers, A., Scopigno, R., Davis, J., Wang, O., ... and Barbosa, J., 2008. Image-Based Empirical Information Acquisition , Scientific Reliability, and Long-Term Digital Preservation for the Natural Sciences and Cultural Heritage. In M. Roussou and J. Leigh *Eurographics*

Tutorials, Crete, 14-18 April 2008. Aire-la-Ville, Switzerland: Eurographics Association. Available from: http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/MUDGE/EG-mudge-tutorial-notes-final.pdf [Accessed January 18, 2013].

Mudge, M., Malzbender, T., Schroer, C., and Lum, M., 2006. New Reflection Transformation Imaging Methods for Rock Art and Multiple-Viewpoint Display. IN: Ioannides, M., Arnold, D., Niccolucci, F., Mania, K. (eds.) *The 37th CIPA International Workshop dedicated on e-Documentation and Standardisation in Cultural Heritage Incorporating:The 7th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, the EUROGRAPHICS Workshop on Graphics and Cultural Heritage, the 1st Euro-Med Conference on IT in Cultural Heritage*, Nicosia, Cyprus, October 30 – November 4 2006. Aire-la-Ville: Eurographics Association, 195–202.

Mudge, M., Voutaz, J. P., Schroer, C. and Lum, M. (2005) Reflection Transformation Imaging and Virtual Representations of Coins from the Hospice of the Grand St. Bernard. IN: Mudge, M. Ryan, N. and Scopigno, R. (eds.) *Proceedings of the 6th International conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, Pisa: 8-11 November 2005. Aire-la-Ville: Eurographics Association, 195–202. Available from: http://dx.doi.org/10.2312/VAST/VAST05/029-039 [Accessed November 16, 2014].

Munoz-Vinas, S. (2005) *Contemporary theory of conservation*. Oxford: Butterworth-Heinemann.

Museum of London (2013) *Handling Museum Objects e-learning tool*. Available from: http://www.museumoflondon.org.uk/Resources/e-learning/handling-museum-objects/ [Accessed 16 November 2014].

Nagy, E.E. (1998) Fills for white marble: properties of seven fillers and two thermosetting resins. *Journal of the American Institute for Conservation*, 37 (1), 69–87. Available from: http://cool.conservation-us.org/jaic/articles/jaic37-01-006.html [Accessed 26 May 2014].

Naoumidou, N., Chatzidaki, M. and Alexopoulou, A. (2008) "ARIADNE" Conservation documentation system: conceptual design and projection on the CIDOC CRM framework and limits. IN: *CIDOC 2008, The Digital Curation of Cultural Heritage*, Athens, 15- 18 September 2008. Available from: http://network.icom.museum/fileadmin/user_upload/minisites/cidoc/ConferencePapers/2008/78_papers.pdf [Accessed May 10, 2014].

National Museums of Scotland (2014) *Tales of a Changing Nation.* Available from: http://www.nms.ac.uk/our_museums/national_museum/explore_the_galleries/scotland_a_changing_nation/tales_of_a_changing_nation.aspx [Accessed 10 May 2014].

Nemeth, O.B. (2009) *Mechanical Fixturing of a Polynomial Texture Mapping Acquisition Device: A Major Qualifying Project*, Bachelor of Science Thesis, Worchester Polytechnic Institute. Available from: https://www.wpi.edu/Pubs/E-project/Available/E-project-043009-222457/unrestricted/PTMMQPONemeth.pdf [Accessed May 26, 2014].

Newell, J. (2012) Old objects, new media: Historical collections, digitization and affect. *Journal of Material Culture,* 17 (3), 287–306. Available from: http://mcu.sagepub.com/cgi/doi/10.1177/1359183512453534 [Accessed 26 May 2013].

Nguyen, H. (2011) *Computed tompography for non-destructive imaging of cultural heritage: X-ray, gamma and neutron sources*, Master Thesis, Queen's University. Available from: http://hdl.handle.net/1974/6713 [Accessed 30 October 2013].

Niven, L., Steele, T. E., Finke, H., Gernat, T. and Hublin, J. J. (2009) Virtual skeletons: using a structured light scanner to create a 3D faunal comparative collection. *Journal of Archaeological Science*, 36 (9), 2018–2023. Available from: http://www.sciencedirect.com/science/article/pii/S0305440309001800 [Accessed 30 October 2012].

Núñez Andrés, A., Buill Pozuelo, F., Regot Marimón, J. and de Mesa Gisbert, A., (2012) Generation of virtual models of cultural heritage. *Journal of Cultural*

Heritage, 13 (1), 103–106. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207411000628 [Accessed 30 October 2012].

O'Connor, S. and Maher, J. (2001) The digitisation of X-radiographs for dissemination, archiving and improved image interpretation. *The Conservator*, 25 (1), 3–15. Available from: http://dx.doi.org/10.1080/01410096.2001.9995159 [Accessed 30 October 2012].

Oddy, W. (1982) Macroscopy in archaeology-the microscope as an extension of the eye. IN: Corfield, M., Foley, K. and Oddy, W. (eds.) *Microscopy in archaeological conservation*. United Kingdom Institute for Conservation, 4-6.

Oddy, W.A. (1992) *The Art of the Conservator*. Washington: Smithsonian Institution Press.

Oddy, W.A. (eds.) (1994) *Restoration: is it acceptable?* London: British Museum.

Oddy, W.A. and Carroll, S. (eds.) (1999) *Reversibility - does it exist?* London: British Museum.

Ogden, S. (1999). *Preservation of library & archival materials*. Andover: Northeast Document Conservation Center.

Öhrström, L., Bitzer, A., Walther, M. and Rühli, F. (2010) Technical note: Terahertz imaging of ancient mummies and bone. *Am. J. Phys. Anthropol.*, 142 (3), 497-500.

Organ, R.M. (1968) *Design for scientific conservation of antiquities*. Washington: Smithsonian Institution Press.

Osterloh, K., Bücherl, T., Hasenstab, A., Rädel, C., Zscherpel, U., Meinel, D., Weidemann, G., Goebbels, J. and Ewert, U. (2007) Fast Neutron Radiography and Tomography of Wood as Compared to Photon Based Technologies. IN: *Proceedings of DIR 2007—International Symposium on Digital Industrial Radiology and Computed Tomography*, Lyon, 25 - 27 June 2007. Available

from: http://www.ndt.net/article/dir2007/papers/33.pdf [Accessed 30 October 2014].

Padfield, J., Saunders, D. and Malzbender, T. (2005) Polynomial Texture Mapping: A New Tool for Examining the Surface of Paintings. *ICOM Committee for Conservation*, 1, 504-510.

Pagi, H. (2011) *RTI viewer for WordPress*. Available from: http://acrg.soton.ac.uk/blog/467/ [Accessed 30 October 2014].

Palleschi, V. (2013) *ICCOM-CNR Attivita per i beni culturali. Laboratorio di Spettroscopia Laser.* PISA: ICCOM. Available from: http://www.confindustriasi.it/files/File/Documenti/DocumentiLavoro/PiattaformaCultura/files05052011/CNR-ICCOM.pdf [Accessed 30 October 2014].

Palma, G. and Callieri, M. (2013) *The coins of Palazzo Blu: The Simoneschi Collection.* Available from: http://vcg.isti.cnr.it/PalazzoBlu/ [Accessed 30 October 2014].

Palma, G., Siotto, E., Proesmans, M., Baldassari, M., Baracchini, C., Batino, S., and Scopigno, R. (2013) Telling the Story of Ancient Coins by Means of Interactive RTI Images Visualization. IN: Earl, G., Sly, T., Chrysanthi, A., Murrieta-Flores, P., Papadopoulos, C., Romanowska, I. and Wheatley, D. (eds.) *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA),* Southampton, 26-29 March 2012. Amsterdam: Amsterdam University Press, 177–184.

Palmas, G., Pietroni, N., Cignoni, P. and Scopigno, R. (2013) A computer-assisted constraint-based system for assembling fragmented objects. IN: *2013 Digital Heritage International Congress*, Marseille, 28 October-1 November 2013. New York: IEEE, 529–536. Available from: http://www.gbv.de/dms/tib-ub-hannover/78685197x.pdf [Accessed 30 October 2014].

Papaodysseus, C., Panagopoulos, T., Exarhos, M., Triantafillou, C., Fragoulis, D. and Doumas, C. (2002) Contour-shape based reconstruction of fragmented, 1600 BC wall paintings. *IEEE Transactions on Signal Processing*, 50 (6), 1277–

1288. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1003053 [Accessed 30 October 2012]

Parry, V. (2013) *The Metropolitan Museum of Art. Making the Invisible Visible: Conservation and Islamic Art. Conserving the Objects from Nishapur*. Available from: http://www.metmuseum.org/exhibitions/listings/2013/invisible-visible/nishapur [Accessed 16 November 2014].

Paterson, M. (2007) *Senses of Touch: Haptics, Affects and Technologies*. Oxford: Berg Publishers

Pavlidis, G., Koutsoudis, A., Arnaoutoglou, F., Tsioukas, V. and Chamzas, C. (2007) Methods for 3D digitization of Cultural Heritage. *Journal of Cultural Heritage*, 8 (1), 93–98. Available from: http://linkinghub.elsevier.com/retrieve/pii/S129620740600121X [Accessed 30 October 2012].

Pearce-Moses, R. (2005) *A glossary of archival and records terminology*. Chicago: Society of American Archivists.

Penn Museum (2012) *In the artifact lab.* Available from: http://www.penn.museum/sites/artifactlab/ [Accessed 17 November 2014].

Pennestrì, E., Pezzuti, E., Valentini, P. P., and Vita, L. (2006) Computer-aided virtual reconstruction of Italian ancient clocks. *Computer Animation and Virtual Worlds*, 17 (5), 565–572. Available from: http://doi.wiley.com/10.1002/cav.155 [Accessed 17 November 2014].

Philippot, P. (1983) Restaurierung aus geisteswissenschaftlicher Sicht, *Oesterreichische zeitschrift fuer kunst und denkmalpflege*, 37 (1-2), 1-9.

Pieraccini, M., Guidi, G. and Atzeni, C. (2001) 3D digitizing of cultural heritage. *Journal of Cultural Heritage*, 2 (1), 63–70. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207401011086 [Accessed July 15, 2014].

Pierret, A., Moran, C.J. and Bresson, L.M. (1996) Calibration and Visualization of Wall-Thickness and Porosity Distributions of Ceramics Using X-radiography and Image Processing. *Journal of Archaeological Science*, 23 (3), 419–428. Available from: http://www.sciencedirect.com/science/article/pii/S0305440396900370 [Accessed 15 July 2014].

Pillay, R. (2011) *IIPMooViewer*. Available from: http://iipimage.sourceforge.net/2011/08/iipmooviewer-2-0-beta/ [Accessed 7 November 2014].

Pintilie, D. C. (2011) Virtual Aesthetic Presentation of Polychrome Sculptures. *e-conservation magazine*, 18, 64–75. Available from: http://www.e-conservationline.com/content/view/981 [Accessed 15 July 2014].

Piquette, K. (2011) Reflectance Transformation Imaging (RTI) and Ancient Egyptian Material Culture. *The CEHAO newsletter,* 7. Available from: http://bibliotecadigital.uca.edu.ar/repositorio/revistas/ancient-egyptian-material-culture-piquette.pdf [Accessed 15 July 2014].

Piquette, K.E. and Macdonald, L.W. (2012) 3D Representations from Reflectance Transformation Image Datasets: A case study from early Egypt. Paper presented at Computer Applications and Quantitative Methods in Archaeology-CAA 2012, Southampton, 26-29 March.

Plenderleith, H.J. (1998) A history of conservation. *Studies in conservation*, 43, 129–143.

Podmaniczky, M.S. (1998) Structural Fills for Large Wood Objects: Contrasting and Complementary Approaches. *Journal of the American Institute for Conservation*, 37 (1), 111–116. Available from: http://cool.conservation-us.org/jaic/articles/jaic37-01-008.html [Accessed 15 July 2014].

Pomaska, G. (2009) Utilization of Photosynth Point Clouds for 3D Object Reconstruction. IN: Takase, Y. (ed.) *Proceedings of the 22nd CIPA symposium on Digital Documentation, Interpretation and Presentation of Cultural Heritage*, Kyoto, 11-15 October 2009. Available from:

http://cipa.icomos.org/fileadmin/template/doc/KYOTO/34.pdf [Accessed 15 July 2014].

Pouliot, B., Fair, L. and Kaplan, L. (2013) *Procedure Manual for the objects laboratory of Winterthur Museum*. Wilmington: University of Delaware. Available from: http://www.connectingtocollections.org/wp-content/uploads/2013/02/Handling_Winterthur.pdf [Accessed 15 July 2014].

Powell, A. (2012) An Ancient Statue, Re-Created: Through Technology, Museum Augments Shard of Ceramic Lion. *Harvard Gazette*, 4 December. Available from: http://news.harvard.edu/gazette/story/2012/12/an-ancient-statue-re-created/ [Accessed 15 July 2014].

Prates, C., Sousa, S., Oliveira, C., and Ikram, S. (2011) Prostate metastatic bone cancer in an Egyptian Ptolemaic mummy, a proposed radiological diagnosis. *International Journal of Paleopathology*, 1 (2), 98–103. Available from: http://www.sciencedirect.com/science/article/pii/S1879981711000271 [Accessed 8 November 2014].

Prudêncio, M. I., Pereira, S., Marques, J. G., Dias, M. I., Esteves, L., Burbidge, C. I., Trindade, M. J. and Albuquerque, M. B. (2012) Neutron tomography for the assessment of consolidant impregnation efficiency in Portuguese glazed tiles (16th and 18th centuries). *Journal of Archaeological Science*, 39 (4), 964–969. Available from: http://www.sciencedirect.com/science/article/pii/S0305440311004249 [Accessed 8 November 2014].

Pugh, G. and Balistreri, J. (2014) *Ceramic 3d printing*. Available from: http://www.ceramic3dprinting.com [Accessed 20 January 2014].

Purdy, B. A., Jones, K. S., Mecholsky, J. J., Bourne, G., Hulbert Jr, R. C., MacFadden, B. J., Church, K.L., Warren, M.W., Jorstad, T.F., Stanford, D.J., Wachowiak, M.J. and Speakman, R. J. (2011) Earliest art in the Americas: incised image of a proboscidean on a mineralized extinct animal bone from Vero Beach, Florida. *Journal of Archaeological Science*, 38 (11), 2908–2913. Available from:

http://www.sciencedirect.com/science/article/pii/S0305440311001828 [Accessed 8 November, 2014].

Pye, E. (2001) *Caring for the Past. Issues in conservation for archaeology and Museums*. London: Jonas and Jonas.

Pye, E. (2004) Understanding objects: The role of touch in conservation. In: Pye, E. (ed.) *The Power of Touch: Handling Objects in Museum and Heritage Contexts*. London: Left Coast Press, 121–135.

Pye, E. (ed.), 2007. *The Power of Touch: Handling Objects in Museum and Heritage Contexts*. London: Left Coast Press.

Radosevic, G. (2010) Laser Scanning Versus Photogrammetry Combined with Manual Post-modeling in Stecak Digitization. IN: Wimmer, M. Hladuvca, J. and Ilcik, M. (eds.) *Proc. 14th Central European Seminar on Computer Graphics*, Budmerice, 10-12 May 2010. Vienna: Vienna University of Technology, 167-174. Available from: http://www.cescg.org/CESCG-2010/proceedings/CESCG-2010.pdf [Accessed 8 November 2014].

Rant, J., Milič, Z., Istenič, J., Knific, T., Lengar, I. and Rant, A. (2006) Neutron radiography examination of objects belonging to the cultural heritage. *Applied radiation and isotopes*, 64 (1), 7–12. Available from: http://www.ncbi.nlm.nih.gov/pubmed/16061388 [Accessed January 18, 2013].

Raskar, R., Tan, K. H., Feris, R., Yu, J., and Turk, M. (2004). Non-photorealistic camera: depth edge detection and stylized rendering using multi-flash imaging. *ACM Transactions on Graphics*, 23 (3), 679-688.

Re, A., Corsi, J., Demmelbauer, M., Martini, M., Mila, G. and Ricci, C. (2015) X-ray tomography of a soil block: a useful tool for the restoration of archaeological finds. *Heritage Science,* 3 (4), 1-7. Available from: http://link.springer.com/article/10.1186/s40494-015-0033-6 [Accessed 16 January 2015].

Redman, J. and Mudge, M. (2007) The simultaneous capture of spectral and textural information. IN: Stovall, S. A. (ed.) *Archiving 2007: final program and*

proceedings, Arlington, 21-24 May 2007. Springfield: Society for Imaging Science and Technology.

Ree, J. (2009) Auto-icons. IN: Richmond, A. and Bracker, A. L. (eds.) *Conservation: Principles, Dilemmas, and Uncomfortable Truths*. Oxford: Butterworth-Heinemann, 1–5.

Reedy, T. and Reedy, C. (1992) Principles of experimental design for art conservation. Newark, Marina del Rey: Getty Conservation Institute. Available from: http://hdl.handle.net/10020/gci_pubs/principles_experimental_design [Accessed 8 November 2014].

Reimers, P. and Riederer, J. (1984) The examination of works of art by means of x-ray computer-tomography (CAT). IN: Froment, D. (ed.) *ICOM Committee for conservation 7th triennial meeting*, Copenhagen, 10-14 September 1984. Paris: International Council of Museums, 77–79.

Remondino, F. and El-Hakim, S. (2006). Image-based 3D Modelling: A Review. *The Photogrammetric Record,* 21 (115), 269-291. Available from: http://onlinelibrary.wiley.com/doi/10.1111/j.1477-9730.2006.00383.x/pdf [Accessed 8 November 2014].

Richens, P. and Herdt, G. (2009) Modelling the Ionic Capital. IN: Cagdas, G. and Colakoglu, B. (eds.) *Computation: the new realm of architectural design: proceedings of the 27th Conference on Education and Research in Computer Aided Architectural Design in Europe*, Istanbul, Turkey, 16-19 September 2009. Glasgow: ECAADE, 809–816.

Risser, E. (1997) A New Technique for the Casting of Missing Areas in Glass Restoration. *Journal of Conservation and Museum Studies*, 3, 11–15. Available from: http://www.jcms-journal.com/article/view/jcms.3973/10 [Accessed 8 November 2014].

Robson, S., Rova, M., Morgan, L., Heuman, J., Heathcote, M., Lees, D., Caner, H. and Mills, C. G. (2008) Measurement of transparent plastic sculptures using photogrammetry, laser scanning and touch probing for conservation purposes. IN: Chen J., Jian J. and Hans-Gerd M., (eds.) *Proceedings of the XXIst ISPRS*

congress, Beijing, 3–11 July 2008. ISPRS, 207–212. Available from: http://www.isprs.org/proceedings/XXXVII/congress/5_pdf/37.pdf [Accessed 8 November 2014].

Rodrigues, M. and Kormann, M. (2012) 3D Scanning of Highly Reflective Surfaces: Issues in Scanning the Museums Sheffield Metalwork Collection. Paper presented at Conference on 3D Scanning and Documentation, Cambridge, 10 - 11 December. Available from: http://shura.shu.ac.uk/6778/ [Accessed 8 November 2014].

Rotroff, S. I. (1991) Attic West Slope Vase Painting. *Hesperia*, 60 (1), 59–102. Available from: http://www.jstor.org/stable/148228 [Accessed 8 November 2014].

Rouillard, J. (2008) Contextual QR Codes. In: Paleologu, C., Noll, J. Antonopoulos, N., Jiang, G., Boyle, D. and Dini, O. (eds.) *The Third International Multi- Conference on Computing in the Global Information Technology, ICCGI 2008, ComP2P 2008: The First International Workshop on Computational P2P Networks: Theory and Practice*, Athens, 27 July - 1 August 2008. Los Alamitos: IEEE, 50–55. Available from: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4591344 [Accessed 8 November 2014].

Rousopoulos, P., Papaodysseus, C., Arabatzis, D., Exarhos, M. and Panagopoulos, M. (2011) Reconstruction of c.1650 B.C. Fragmented Wall Paintings by Exploitation of the Thematic Content. *International Journal of Imaging and Robotics*, 5 (S11), 1–17. Available from: http://www.ceser.in/ceserp/index.php/iji/article/view/2814 [Accessed 8 November 2014].

Rowe, J., Razdan, A. and Simon, A. (2003) Acquisition, representation, query and analysis of spatial data: a demonstration 3D digital library. IN: Marshall, C. C., Henry, G. and Delcambre, L. (eds.) *Proceedings of 2003 Joint Conference on Digital Libraries*, Houston, Texas, 27-31 May 2003. Los Alamitos: IEEE, 147–158. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1204855 [Accessed 8 November 2014].

Rudenstine, A. Z. and Whalen, T. P. (2006) Conservation Documentation in Digital Form: A Dialogue about the Issues. Conservation Perspectives, *The GCI Newsletter*, 21 (2), 26-29. Available from: http://www.getty.edu/conservation/publications_resources/newsletters/pdf/v21n2.pdf [Accessed 8 November 2014].

Ruhli, F.D. (2007) *Mobile NMR and Cultural Heritage, University of Zürich*. Available from: http://www.nmr-mouse.de/download/CMMR6_Bluemich_Talk-Mobile_NMR_and_Cultural_Heritage.pdf [Accessed 8 November 2014].

Rusinkiewicz, S., Cole, F., DeCarlo, D. and Finkelstein, A. (2008) Line drawings from 3D models. IN: *ACM SIGGRAPH 2008 classes (SIGGRAPH '08)*, Article 39, New York: ACM. Available from: http://doi.acm.org/10.1145/1401132.1401188 [Accessed 8 November 2014].

Sá, A. M., Rodriguez-Echavarria, K., Griffin, M., Covill, D., Kaminski, J., and Arnold, D. B. (2012). Parametric 3D-fitted frames for packaging heritage artefacts. IN: Arnold, D., Kaminski, J., Niccolucci, F. and Stork, A. (eds.) *VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, Brighton, 19-21 November 2012. Aire-la-Ville: Eurographics Association, 105-112. Available from: http://culturalinformatics.org.uk/files/papers/SemanticallyRich3D2012.pdf [Accessed 20 January 2014].

Sagiroglu, M.S. and Erçil, A. (2006) A texture based matching approach for automated assembly of puzzles. IN: Tang, Y.Y., Wang, S.P, Lovette, G., Yeung, D.S. and Yan, H. (eds.) *18th International Conference on Pattern Recognition ICPR 2006*, Hong Kong, 20-24 August 2006. Los Alamitos: IEEE, 1036 - 1041. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=andarnumber=1699703 [Accessed 8 November 2012].

Salonia, P., Scolastico, S., Pozzi, A., Marcolongo, A. and Messina, T. L. (2009) Multi-scale cultural heritage survey: Quick digital photogrammetric systems. *Journal of Cultural Heritage*, 10 (Supplement 1), 59–64. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207409001381 [Accessed 8 November 2012].

Schaeffer, T. (2001) *Effects of light on materials in collections*. Los Angeles: Getty Conservation Institute.

Schiffer, M. B. and Miller, A. (1999) *The Material Life of Human Beings: Artifacts, Behavior, and Communication*. London: Routledge.

Schinzel, H., (1999) Restoration - a kaleidoscope through history. IN: Oddy, W. and Carroll, S. (eds.) *Reversibility: Does it exist?* London: British Museum, 43-45.

Schreiber, T. (1999). *Athenian vase construction*. Malibu: J. Paul Getty Museum.

Schroer, C. (2012) Advanced Imaging Tools for Museum and Library Conservation and Research. *Bulletin of the American Society for Information Science and Technology*, 38 (3), 38–42. Available from: http://www.asis.org/Bulletin/Feb-12/FebMar12_Schroer.html [Accessed 12 December 2013].

Schroer, C. and Mudge, M. (2012) Advances in the computational photography tools: Reflectance Transformation Imaging (RTI) and Algorithmic Rendering (AR). Paper presented at Computer Applications and Quantitative Methods in Archaeology-CAA 2012. Southampton, 26-29 March.

Scott, D.A. and Dodd, L.S. (2002) Examination, conservation and analysis of a gilded Egyptian bronze Osiris. *Journal of Cultural Heritage*, 3 (4), 333–345. Available from: http://www.sciencedirect.com/science/article/pii/S1296207402012384 [Accessed 12 December 2013].

Selmo, D. (2013) *Underwater Reflectance Transformation Imaging…a success*. Available from: http://cma.soton.ac.uk/blog/2013/05/underwater-reflectance-transformation-imaging-a-success/ Accessed 12 November 2013].

Shapeways (2015) Elasto plastic material. Available from: http://www.shapeways.com/materials/elasto-plastic [Accessed 20 January 2015]

Shashoua, Y. (2008) *Conservation of plastics*. Amsterdam: Elsevier / Butterworth-Heinemann.

Shelley, M. (1987) *The care and handling of art objects*. New York: Metropolitan Museum of Art.

Shin, D. H., Lee, I. S., Kim, M. J., Oh, C. S., Park, J. B., Bok, G. D. and Yoo, D. S. (2010) Magnetic resonance imaging performed on a hydrated mummy of medieval Korea. *Journal of Anatomy*, 216 (3), 329–34. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2829391/?tool=pmcentrez [Accessed 12 December 2013].

Shin, H., Doumas, C., Funkhouser, T., Rusinkiewicz, S., Steiglitz, K., Vlachopoulos, A. and Weyrich,T. (2012) Analyzing and simulating fracture patterns of theran wall paintings. *Journal on Computing and Cultural Heritage*, 5 (3), 1–14. Available from: https://www.cs.princeton.edu/~funk/shin12.pdf [Accessed 31 January 2013].

Simon Chane, C., Mansouri, A., Marzani, F. S. and Boochs, F. (2013) Integration of 3D and multispectral data for cultural heritage applications: Survey and perspectives. *Image and Vision Computing*, 31 (1), 91-102. Available from: http://www.sciencedirect.com/science/article/pii/S0262885612001862 [Accessed 21 November 2014].

Skinner, L. (2009) Bronze Age metalwork from central Norway: some examples of ancient and modern repair. IN: Ambers, J., Higgit, C., Harrison, L. and D. Saunders (eds.) *Holding it all together: Ancient and Modern Approaches to Joining, Repair and Consolidation*, London, 21-22 February 2008. London: Archetype, 31–34.

Smith, R.D. (1988) Reversibility: A questionable philosophy. *Restaurator*, 9 (4), 199–207.

Smith, R.D. (1999) Drawing the line - Reversibility and compromise in the conservation of arms and armour. IN: Oddy, W. and Carroll, S. (eds.) *Reversibility: Does it exist?* London: British Museum, 7–9.

Smith, S. (1998) British Bronze age pottery: an overview of deterioration and current techniques of conservation at the British museum. *The Conservator*, 22 (1), 3–11. Available from: http://www.tandfonline.com/doi/abs/10.1080/01410096.1998.999512 [Accessed 18 January 2013].

Sodini, N., Dreossi, D., Chen, R., Fioravanti, M., Giordano, A., Herrestal, P., Rigon, L. and Zanini, F. (2012) Non-invasive microstructural analysis of bowed stringed instruments with synchrotron radiation X-ray microtomography. *Journal of Cultural Heritage*, 13 (3, Supplement), 44–49. Available from: http://www.sciencedirect.com/science/article/pii/S129620741200088X [Accessed 12 November 2013].

Soe, S.P., Eyers, D.R., Jones, T. and Nayling, N. (2012) Additive manufacturing for archaeological reconstruction of a medieval ship. *Rapid Prototyping Journal*, 18 (6), 443–450. Available from: http://www.emeraldinsight.com/10.1108/13552541211271983 [Accessed 7 November 2013].

Song, M., Elias, T., Mueller-Wittig, W. and Chan, T.K.Y. (2005) Using the Chinese Calligraphy brush as a tangible user interface tool in virtual heritage scenarios. *Computers and Graphics*, 29 (1), 41–48. Available from: http://www.sciencedirect.com/science/article/pii/S009784930400192X [Accessed 12 December 2013].

Staimer, M. (2012) *Why Digital Data Permanence is such an Urgent Difficult Problem and How to effectively solve it how to effectively Fix It*. Beaverton, OR: Dragon Slayer Consulting.

Stelzner, J., Ebinger-Rist, N., Peek, C., Schillinger, B. (2010) The application of 3D computed tomography with X-rays and neutrons to visualize archaeological objects in blocks of soil. *Studies in Conservation*, 55 (2), 95-106.

Stephen, A. (2001) The Contemporary Museum and Leisure: Recreation As a Museum Function. *Museum Management and Curatorship*, 19 (3), 297–308. Available from: http://dx.doi.org/10.1080/09647770100601903 [Accessed 12 December 2013].

Stocks, D. A. (1993) Making stone vessels in ancient Mesopotamia and Egypt. *Antiquity*, 67 (256), 596–603. Available from: http://antiquity.ac.uk/Ant/067/0596/Ant0670596.pdf [Accessed 12 December 2013].

Stødkilde-Jørgensen, H., Jacobsen, N.O., Warncke, E., and Heinemeier, J. (2008) The intestines of a more than 2000 years old peat-bog man: microscopy, magnetic resonance imaging and 14 C-dating. *Journal of Archaeological Science*, 35 (3), 530-534. Available from: http://www.sciencedirect.com/science/article/pii/S0305440307000957 [Accessed 12December 2013].

Stratis, J.A., Makarona, C., Lazidou, D., Gómez Sánchez, E., Koutsoudis, A. Pamplona, M., Pauswein, R., Pavlidis, G., Simon, S. and Tsirliganis, N. (2013) Enhancing the examination workflow for Byzantine icons: Implementation of information technology tools in a traditional context. *Journal of Cultural Heritage*, 15 (1), 1–7. Available from: http://www.sciencedirect.com/science/article/pii/S1296207412001252 [Accessed 16 January 2013].

Sullivan, S.M. (2011) *Analytical methods for the extraction of content from high resolution 3D data sets: Epigraphical applications to the Drakon Stele*, Master of Arts Thesis, University of Arkansas.

Svoboda, M. (2005) *Case Study: A Funerary Jar*. Available from: http://www.getty.edu/art/exhibitions/fragment_to_vase/lekythos.html [Accessed 16 November 2014].

Sylaiou, S., Liarokapis, F., Kotsakis, K. and Patias, P. (2009) Virtual museums, a survey and some issues for consideration. *Journal of Cultural Heritage*, 10 (4), 520–528. Available from: http://www.sciencedirect.com/science/article/pii/S1296207409000880 [Accessed 16 January 2013].

Tan, L., and Wang, N. (2010) Future internet: The Internet of Things. IN: Desheng, W, Ruofeng, W. and Yie, X. (eds.) *Proceedings of 3rd international conference on advanced computer theory and engineering (ICACTE'10), volume*

5, Chengdu, 20-22 August 2010. New York: IEEE, 376-380. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5579543 [Accessed 16 January 2013].

Taylor, J., Beraldin, J. A., Godin, G., Baribeau, R., Cournoyer, L., Boulanger, P., Rioux, M., and Domey, J. (2002) Culture as a Driving Force for Research and Technology Development: A Decade's Experience of Canada's NRC 3D Technology, IN: Hemsley, J. Cappellini, V. and Stank, G. (eds.) *EVA London 2002. Electronic Visualisation & the Arts*, London, 24-25 July 2002. London: EVA Conferences International.

Themelis, P. and Touratsoglou, I. (1997) *Tafoi tou Derveniou*, Athens: TAPA.

Theofanopoulou, O. and Tossiou, S. (2007) Gap-filling and In-Painting: Drawing the line. The example of a Red-figure Amphora from the Benaki Museum Collection. IN: Bentz, M. and Kästner, U. (eds.) *Konservieren oder restaurieren: die Restaurierung griechischer Vasen von der Antike bis heute*. Mu̇nchen: Beck, 133–145.

Thimmesch, D. (2014) *UCLA and Architected Materials 3D Print Protective Material for Helmets, in NFL's Head Health Challenge*. Available from: http://3dprint.com/26399/head-health-challenge-lattice/ [Accessed 20 January 2015]

Thomson, G. (1994) *The Museum Environment*, 2nd edition. London: Butterworths.

Tinkercad (2015) *3D printing material guide.* Available from: www.tinkercad.com [Accessed 20 January 2015]

Toler-Franklin, C., Finkelstein, A. and Rusinkiewicz, S. (2007) Illustration of complex real-world objects using images with normals. IN: Gooch, B. Agrawala, M. and Deussen, O. (eds.) *Proceedings of the 5th international symposium on Non-photorealistic animation and rendering*, San Diego, 4-5 August 2007. New York: ACM, 111-119. Available from: http://dl.acm.org/citation.cfm?doid=1274871.1274889 [Accessed January 16 November 2011].

Toracca, G. (1982) The scientist's role in historic preservation with particular reference to stone conservation. IN: *Conservation of historic stone buildings and monuments.* Washington: The National Academies Press, 13–21. Available from: http://www.nap.edu/openbook.php?record_id=514&page [Accessed 17 November 2014].

Townsend, J. H. (2010) Evidence for varnishes used by British artists in the nineteenth century. *Journal of the Institute of Conservation*, 33 (2), 147–161. Available from: http://www.tandfonline.com/doi/abs/10.1080/19455224.2010.498322 [Accessed 16 January 2013].

Troalen L., Tate J., Connell, M, Loomis K., Kirk, S., and van Beek E.J.R. (2011) Revealing collections large and small by CT scans at National Museums of Scotland. Paper presented at Imaging in Conservation: Looking at artefacts under new light. ICON Archaeology and Science Group, STFC Rutherford Appleton Laboratory, Harwell Campus, Oxfordshire, 10-11 November.

UCL (2011) *Qrator.* Available from: http://www.qrator.org/ [Accessed 17 November 2014].

UKIC (1996) *UKIC Code of Ethics and Rules of Practice*, London: United Kingdom Institute for Conservation of Historic and Artistic Works.

uQRme (2013) *Why should museums work together with QR code generators?* Available from: http://uqr.me/2013/02/qr-codes-in-museums/ [Accessed 16 November 2014].

Vaccaro, A.M., Coreman, P., Torraca, G., and Urbani, G. (1996) The role of science and technology. IN: Stanley-Price, N., Talley, M. K. and Vaccaro, A. M., (eds.) *Historical and philosophical issues in the conservation of cultural heritage*. Los Angeles: Getty Conservation Institute, 424–450.

Valergas, V. (2014) U*se of Transmitted imaging and RTI for the study of ancient texts*, Master of Science Thesis, University of Southampton.

Van der Linden, V., Van de Casteele, E., Thomas, M. S., De Vos, A., Janssen, E., and Janssens, K., 2009. Analysis of micro computed tomography images; a

look inside historic enamelled metal objects. Applied Physics A, 98 (2), 385–392. Available from:http://www.springerlink.com/index/10.1007/s00339-009-5394-9 [Accessed January 18, 2013].

Van Langh, R., Lehmann, E., Hartmann, S., Kaestner, A., and Scholten, F., 2009. The study of bronze statuettes with the help of neutron-imaging techniques. Analytical and bioanalytical chemistry, 395 (7), 1949–59. Available from: http://link.springer.com/article/10.1007/s00216-009-3058-4/fulltext.html [Accessed January 18, 2013].

Vargiolu, R., Morero, E., Boleti, A., Procopiou, H., Pailler-Mattei, C. and Zahouani, H. (2007) Effects of abrasion during stone vase drilling in Bronze Age Crete. *Wear*, 263 (1–6), 48–56. Available from: http://www.sciencedirect.com/science/article/pii/S0043164807004462 [Accessed 17 November 2014].

Vaughan, W. (2012). *Digital modeling*. Berkeley, Calif.: New Riders.

Vazquez-Briseno, M., Hirata, F. I., de Dios Sanchez-Lopez, J., Jimenez-Garcia, E., Navarro-Cota, C. and Nieto-Hipolito, J. I. (2012) Using RFID / NFC and QR-Code in Mobile Phones to Link the Physical and the Digital World. IN: Deliyannis, I. (ed.) *Interactive Multimedia*. Rijeka: InTech, 219–242. Available from: http://www.intechopen.com/books/interactive-multimedia/using-rfid-nfc-and-qr-code-in-mobile-phones-to-link-the-physical-and-the-digital-world [Accessed 27 November 2014].

Velios, A. and Harrison, J. (2007) *Digital Reconstruction of Fragmented Archaeological Objects*. Studies in Conservation, 52 (1), 19–36.

Verhoeven, G. (2008) Imaging the invisible using modified digital still cameras for straightforward and low-cost archaeological near-infrared photography. *Journal of Archaeological Science*, 35 (12), 3087–3100. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440308001325 [Accessed 27 November 2012].

Verhoeven, G.J. and Schmitt, K.D. (2010) An attempt to push back frontiers – digital near-ultraviolet aerial archaeology. *Journal of Archaeological Science*, 37

(4), 833–845. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0305440309004312 [Accessed 16 January 2013].

Verri, G. (2009) The spatially resolved characterisation of Egyptian blue, Han blue and Han purple by photo-induced luminescence digital imaging. *Analytical and bioanalytical chemistry*, 394 (4), 1011–21. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19234690 [Accessed 11 December 2012].

Verri, G., Collins, P., Ambers, J., Sweek, T. and Simpson, S. J. (2009) Assyrian colours: pigments on a neo-Assyrian. *The British Museum - Technical Research Bulletin*, 3, 57-62. Available from: https://www.britishmuseum.org/pdf/BMTRB%203%20Verri%20et%20al.pdf [Accessed 16 January 2014].

Vidimče, K., Wang, S. P., Ragan-Kelley, J. and Matusik, W. (2013). OpenFab: A Programmable Pipeline for Multi-Material Fabrication. *ACM Transactions on Graphics*, 32 (4):136

Vienna University of Technology (2014) *Orient: A universal photogrammetric adjustment system.* Available from: http://photo.geo.tuwien.ac.at/software/orient-orpheus/ [Accessed 20 January 2014].

Viénot, F., Coron, G. and Lavédrine, B. (2011) LEDs as a tool to enhance faded colours of museums artefacts. *Journal of Cultural Heritage*, 12(4), 431-440. Available from: http://dx.doi.org/10.1016/j.culher.2011.03.007 [Accessed 16 November 2014].

Villers, C. (2004) Post minimal intervention. *The Conservator*, 28 (1), 3–10. Available from: http://www.tandfonline.com/doi/abs/10.1080/01410096.2004.9995197 [Accessed 12 February 2013].

VISICS K.U.Leuven (2014) *ARC3D Automatic Reconstruction Cloud Convert your images into 3D.* Available from: http://www.arc3d.be/ [Accessed 20 January 2014].

Wachowiak, M. and Webb, E.K. (2012) *Application of Current 3D and Pseudo-3D Imaging for Conservation. Smithsonian Museum Conservation Institute. Washington D.C.* Available from: http://ncptt.nps.gov/blog/application-of-current-3d-and-pseudo-3d-imaging-for-conservation/ [Accessed 12 February 2013].

Wachowiak, M.J. and Karas, B.V. (2009) 3D scanning and replication for museum and cultural heritage applications. *Journal of the American Institute for Conservation*, 48 (2), 141–158. Available from: http://www.maneyonline.com/doi/abs/10.1179/019713609804516992 [Accessed 12 February 2013].

Walker, A. (2013) *Beyong the looking glass, object handling and access to museum collections*, PhD Thesis, University of Southampton.

Walker, G. C., Bowen, J. W., Matthews, W., Roychowdhury, S., Labaune, J., Mourou, G., ... and Jackson, J. B. (2013) Sub-surface terahertz imaging through uneven surfaces: visualizing Neolithic wall paintings in Çatalhöyük. *Optics express*, 21 (7), 8126-8134. Available from: http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-21-7-8126 [Accessed 16 November 2014].

Walsh, C. (2014) A light touch for Rothko murals. *Harvard Gazette*, 20 May. Available from: http://news.harvard.edu/gazette/story/2014/05/a-light-touch-for-rothko-murals/ [Accessed 23 November 2014].

Warda, J. (ed.) (2011) *The AIC Guide to Digital Photography and Conservation Documentation*, 2nd edition. Washington: American Institute for Conservation.

Warnier, C., Verbruggen, D., Ehmann, S. and Klanten, R. (2014) *Printing things*. Berlin: Gestalten.

Watson, J.R. (2010) The Elements of Conservation: A Conceptual Model. IN: Williams E. and Peachey C. (eds.) *The Conservation of Archaeological Materials:*

Current Trends and Future Directions. BAR International Series 2116. Oxford: Archaeopress, 11–15.

Waugh, A. (1973) *Sundials: Their Theory and Construction*. London: Dover Publications.

Webb, E.K. and Wachowiak, M. (2011) *Quadra Flash Mantis for Reflectance Transformation Imaging (RTI)*. Available from: http://www.si.edu/content/mciimagingstudio/papers/quadriflashmantis_rti_technical_note.pdf [Accessed 23 November 2014].

Webber, S.L. (2008) Technical Imaging of Paintings. *Williamstown Art Conservation Center, Technical Bulletin.* Available from: http://www.williamstownart.org/techbulletins/images/WACC Imaging of Paintings.pdf [Accessed 23 November 2014].

Welbourne, E. Battle, L., Raymer, S., Balazinska, M., Borriello, G., Cole, G., Gould, K. and Rector, K. (2009) Building the internet of things using RFID: the RFID ecosystem experience. *IEEE Internet computing*, 13 (3), 48–55. Available from: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4907686 [Accessed 8 November 2012].

Willis, A.R. and Cooper, D.B. (2008) Computational Reconstruction of Ancient Artifacts. *IEEE Signal processing magazine*, 25 (4), 65–83. Available from: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4545850 [Accessed 8 November 2013].

Winkenbach G.and Salesin D.H. (1994) Computer-generated pen-and-ink illustration. IN: Schweitzer, D., Glassner, A. and Keeler, M. (eds.), *SIGGRAPH '94 Proceedings of the 21st annual conference on Computer graphics and interactive techniques,* Orlando, FL, USA, 24-29 July 1994. New York: ACM, 91-100. Available from: http://doi.acm.org/10.1145/192161.192184 [Accessed 26 October 2012].

Witte, Y. De, Cnudde, V., Pieters, K., Masschaele, B., Dierick, M., Vlassenbroeck, J., Van Hoorebeke, L. and Jacobs, P. (2008) X-ray micro-CT applied to natural building materials and art objects. *XRay Spectrometry*, 37 (4), 383–387.

Available from: http://dx.doi.org/10.1002/xrs.1071 [Accessed 8 November 2012].

Yastikli, N. (2007) Documentation of cultural heritage using digital photogrammetry and laser scanning. *Journal of Cultural Heritage*, 8 (4), 423–427. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207407001082 [Accessed 8 November 2012].

Yilmaz, H.M., Yakar, M., Gulec, S.A. and Dulgerler, O.N. (2007) Importance of digital close-range photogrammetry in documentation of cultural heritage. *Journal of Cultural Heritage*, 8 (4), 428–433. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207407001094 [Accessed 8 November 2012].

Yılmaz, U., Özün, O., Otlu, B., Mülayim, A., and Atalay, V. (2003). Inexpensive and robust 3D model acquisition system for three-dimensional modeling of small artifacts. IN: Altan, M. (ed.) *New Perspectives to save Cultural Heritage. Proceedings of the XIXth International Symposium, CIPA 2003*, Antalya, 30 September - 4 October 2003. Istanbul, Turkey: CIPA. Available from: http://cipa.icomos.org/fileadmin/template/doc/antalya/80.pdf [Accessed 26 May 2014].

Yoder, D. (2013) Invisible Culture: The Use of Soft X-ray Radiography in Perishable Research. *Journal of Archaeological Method and Theory*, 20 (1), 1–17. Available from: http://dx.doi.org/10.1007/s10816-011-9123-2 [Accessed 23 November 2014].

Yu, C., Groza, T. and Hunter, J. (2011) High Speed Capture, Retrieval and Rendering of Segment-Based Annotations on 3D Museum Objects. IN: Xing, C., Crestani, F. and Rauber, A. (eds.) *Digital Libraries: For Cultural Heritage, Knowledge Dissemination, and Future Creation. Proceedings of 13th International Conference on Asia-Pacific Digital Libraries, ICADL 2011*, Beijing, 24-27 October 2011. Heidelberg: Springer, 5–15. Available from: http://link.springer.com/chapter/10.1007/978-3-642-24826-9_5 [Accessed 23 May 2014].

Zányi, E., Schroer, C., Mudge, M. and Chalmers, A. (2007) Lighting and byzantine glass tesserae. IN: Bowen, J., Keene, S. and MacDonald, L. (eds.) *EVA London 2007*, *Electronic Visualisation & the Arts*, London, 21-22 July 2007. London: EVA Conferences International. Available from: http://culturalheritageimaging.org/What_We_Do/Publications/eva2007/EVA_2007.pdf [Accessed 23 January 2014].

Zhang, X., Blaas, J., Botha, C., Reischig, P., Bravin, A. and Dik, J. (2012) Process for the 3D virtual reconstruction of a microcultural heritage artifact obtained by synchrotron radiation CT technology using open source and free software. *Journal of Cultural Heritage*, 13 (2), 221–225. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1296207411000860 [Accessed 18 January 2013].

Zimmer, R. and Jefferies, J. (2007) Accessing material art through technologies of mediation and immediation. *Futures*, 39 (10), 1178–1190. Available from: http://www.sciencedirect.com/science/article/pii/S0016328707000821 [Accessed 23 January 2014].

Zolfagharifard, E. (2013) The rise of multi-material 3D printing. *The engineer*, 9 May. Available from: http://www.theengineer.co.uk/channels/design-engineering/in-depth/the-rise-of-multi-material-3d-printing/1016242.article [Accessed 23 January 2014].

Zweifel, L., Büni, T. and Rühli, F.J. (2009) Evidence-based palaeopathology: meta-analysis of PubMed-listed scientific studies on ancient Egyptian mummies. *Homo internationale Zeitschrift fur die vergleichende Forschung am Menschen*, 60 (5), 405–427. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19744651 [Accessed 23 January 2014].

Appendices

Appendix A

A.1 Conservation Processes

Clavir has noted the differences and disagreements of conservation with other museum sectors but also emphasized conservation's contribution to values (Clavir, 2002). Without conservation the museum could not manage to achieve its four classic functions; to collect, to preserve, to research and to display (Ward, 1986). Nevertheless, conservation remains the least known period of the artefact's museum life, not only for the general public, but also for cultural heritage professionals. This is due to the fact that conservation activities turn to be less easily detectable, following minimal-intervention approaches. Moreover, a factor that affects the dissemination and broader understanding of conservation is that it is the youngest of the museum disciplines. Although the ancient origins of conservation were described from Classical writers, such as Pliny, Vitrubious and Pausanias (Keck, 1996), as a scientific discipline on its own conservation emerged during the 19th century, with the formation of the Chemical Laboratory of the Royal Museums of Berlin in 1888 in the State Museum of Berlin by Dr Friedrich Rathgen (Gilberg, 1987; Plenderleith, 1998).

Conservators, involved either in remedial treatment, restoration activities or preventive measures, have to deal with the inevitable materials degradation, which starts just after the creation of the artefact, continues with its use and burial and deteriorates with discovery-excavation. Contemporary conservation conceptual models set as objectives of conservation the accessibility, durability, integrity and practicality, achieved via a set of actions, such as investigation, intervention, prevention and communication (Watson, 2010). Conservation was simply categorized as a sequence of composition, deterioration, and treatment according to Reedy, who stated that the three-part division could capture the vast majority of conservation research literature published by 1992 (Reedy and Reedy, 1992). From a contemporary perspective this categorization is an oversimplification. More recently presented schemes include procedures such as registration, examination, diagnosis and development of a conservation methodology, conservation-restoration and

presentation – dissemination (Chatzidakis, 2001). These procedures do not follow a sequential order, but can be repeated over time, according to the specific needs of each project. Consequently, conservation can be conceived as a complex matrix of processes, which are cross-linked in various ways. Appelbaum describes conservation as an eight step process: characterization of the object, reconstruction of object's history, determination of the ideal state, establishment of the goal of treatment, decision making (materials and methods), pre-treatment documentation, treatment, and documentation (Appelbaum, 2007).

The full characterization of the object includes material and non-material aspects as well as object-specific and non-specific information. The object specific material data are retrieved from the object itself after the correct interpretation of physical examination, analysis, imaging and testing, while the object specific non-material data are retrieved from the history of the object and its values analysis. The non-object specific data are retrieved from literature review and archives research and include information about material aspects, such as methods of manufacture, materials, techniques and deterioration, as well as non-material aspects, such as data about related objects and art history (Appelbaum, 2007). Consequently, the main processes that take place during the characterization of the object are the examination-investigation of the object and archives research.

A.1.1 Investigation

Analysis, examination and diagnostics are the main attributes of objects investigation.

- Analysis or scientific investigation (analytical techniques) is physical, chemical and biological analyses and usually provides qualitative or/and quantitative data about the composition.
- Examination of materials and methods (examination techniques) involves the study of the artefact and the interpretation of information related to material and manufacture.
- Diagnostic examination consists of assessment of the condition (the nature and extent of alterations) of cultural heritage and diagnosis (evaluation of the causes of deterioration).

According to the second article of the Definition of the Profession published by ICOM-CC, these preliminary procedures determine

> '*the documentary significance of an artefact; original structure and materials; the extent of its deterioration, alteration, and loss; and the documentation of these findings*' (ICOM, 2010, p.2).

Investigation consists of visual analysis and the elemental-molecular composition of the objects. The former group includes microscopy (stereomicroscopy, transmitted and reflected microscopy, scanning electron microscopy) and imaging techniques (multispectral and x-radiography). The latter group refers to quantitative, qualitative and isotopic analysis for inorganic materials and spectrometric chromatographic techniques for materials of organic nature.

A.1.2 Archives research

Archives research (or literature survey and reading) is the action of retrieving information related to the artefact under examination from the archive (institutional or general archive) or information about artefacts which present similarities in any aspect (material, date, area, shape, typology, style, decorative features, geographical area, degradation, construction techniques). Many times it is omitted, postponed or underestimated, although it is a very significant stage of artefact analysis, which should be executed before treatment, in order to influence conservation decisions and methodology.

A.1.3 Treatment proposal

The interpretation of the examination findings in addition to the data retrieved from the archives research should be combined with the biographical and values analysis of the object in order to help the conservator determine the ideal state, establish the goal of treatment and then decide the type and the extent of treatment needed (treatment proposal). The treatment plan provides the necessary justification for the treatment, which takes the form of conservation, preventive conservation or restoration.

A.1.4 Conservation treatment

Conservation consists mainly of direct actions carried out on with the aim of stabilising condition and retarding further deterioration.

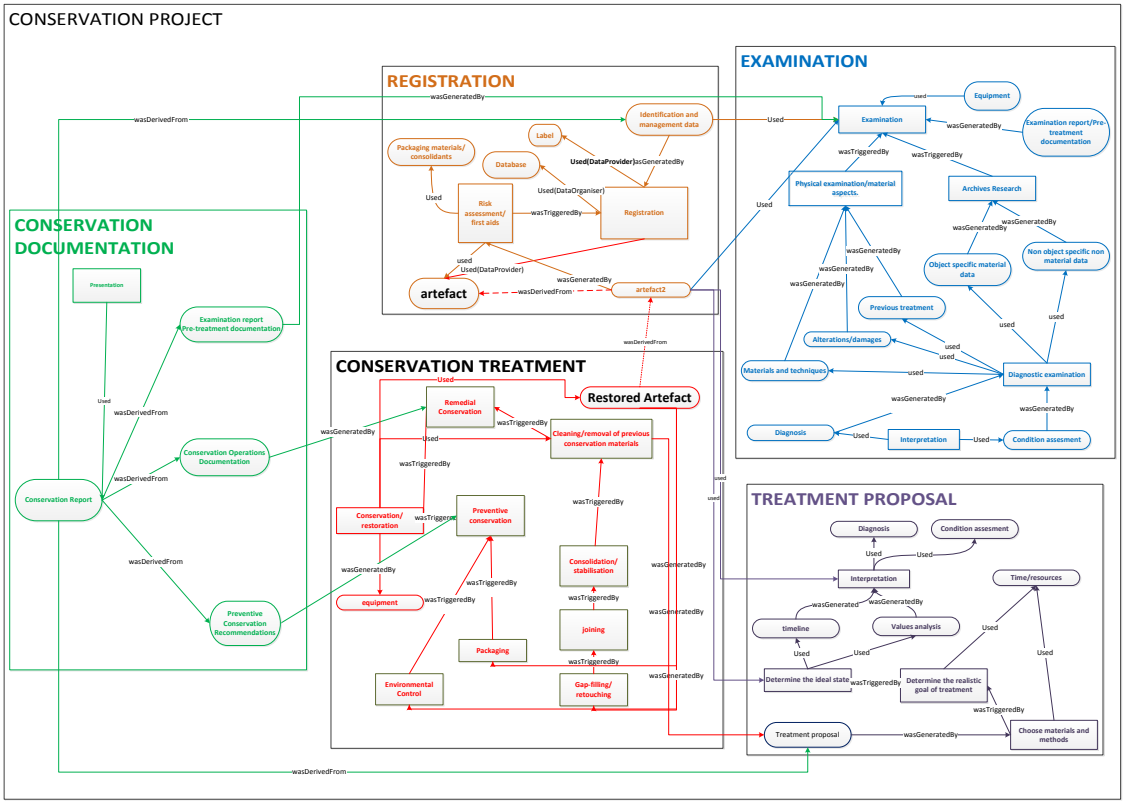
Preventive conservation consists of indirect action to pace the rate of deterioration and prevent further damage from environmental conditions (temperature, relative humidity, and light), handling, transport, use, storage and display.

Restoration seeks to return the object to its original state with respect to its aesthetic, historic and physical properties. The most frequent operations are the joining of fragments, partial or complete infilling of missing areas, reshaping and in painting or retouching. Also, restoration involves the design of mounts for storage or display.

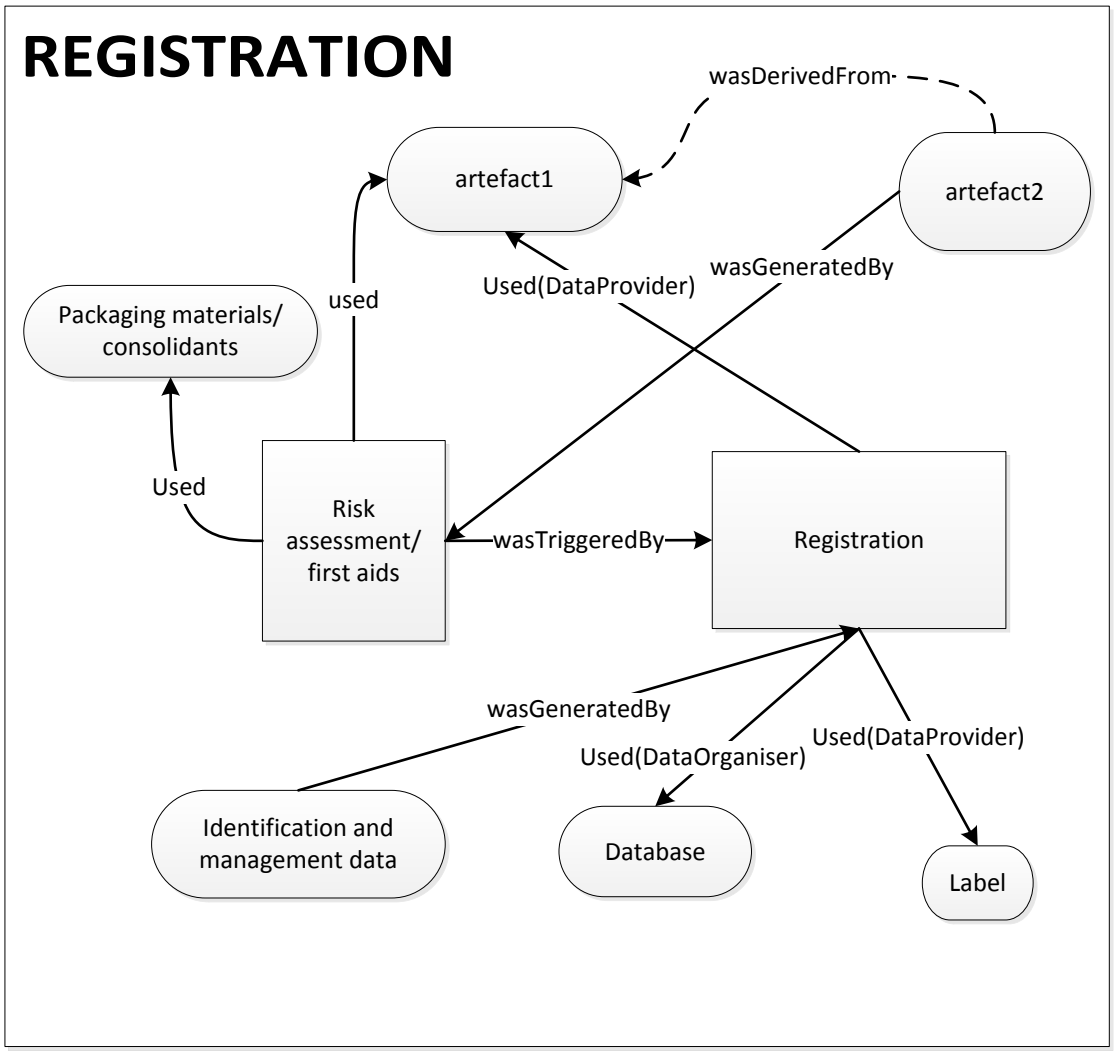
A.1.5 Conservation report

The whole process is documented in conservation reports. Documentation is an obligation which includes the production and maintenance of accurate, complete, and permanent records of examination, sampling, scientific investigation, and treatment in both written and pictorial form (AIC, 1994). The preservation and sharing of such records and experience is the conservator's responsibility and considered an action which contributes to the growth and progression of the profession to the highest standards by continuing to develop knowledge and skills (UKIC, 1996).

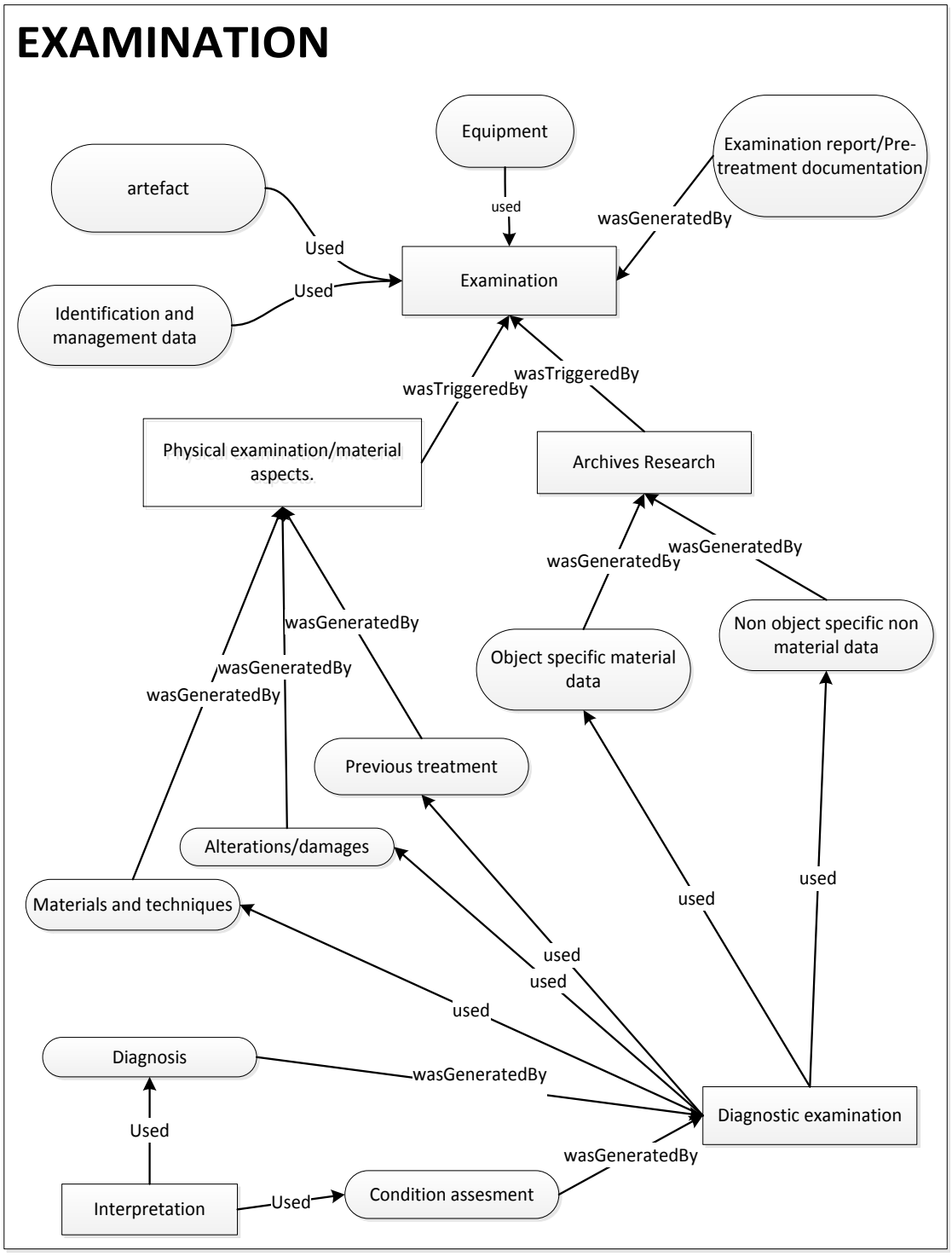
A.1.6 Open Provenance Graphs



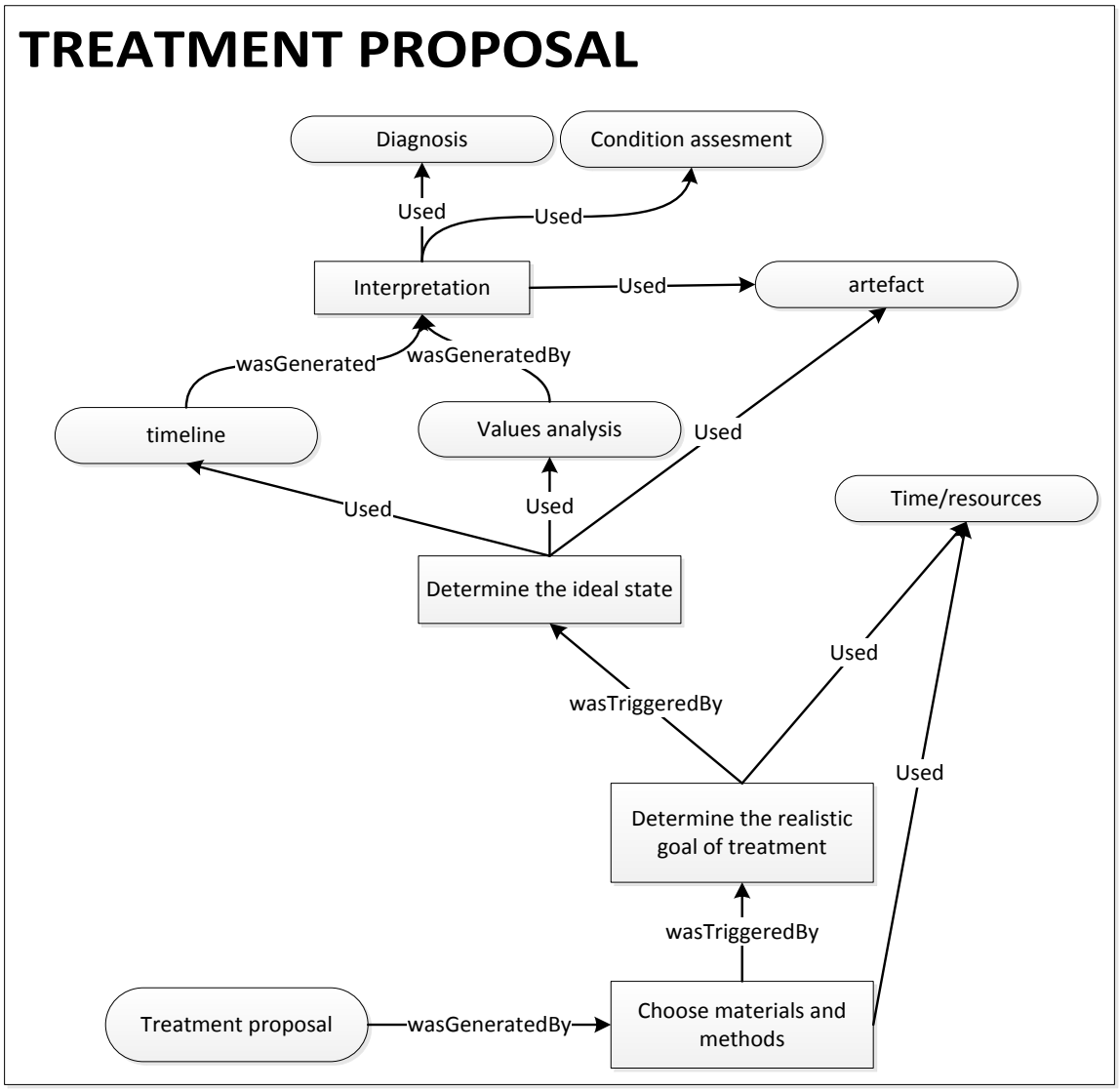
Graph 52: OPM Graph of a conservation project (Graph author's own).



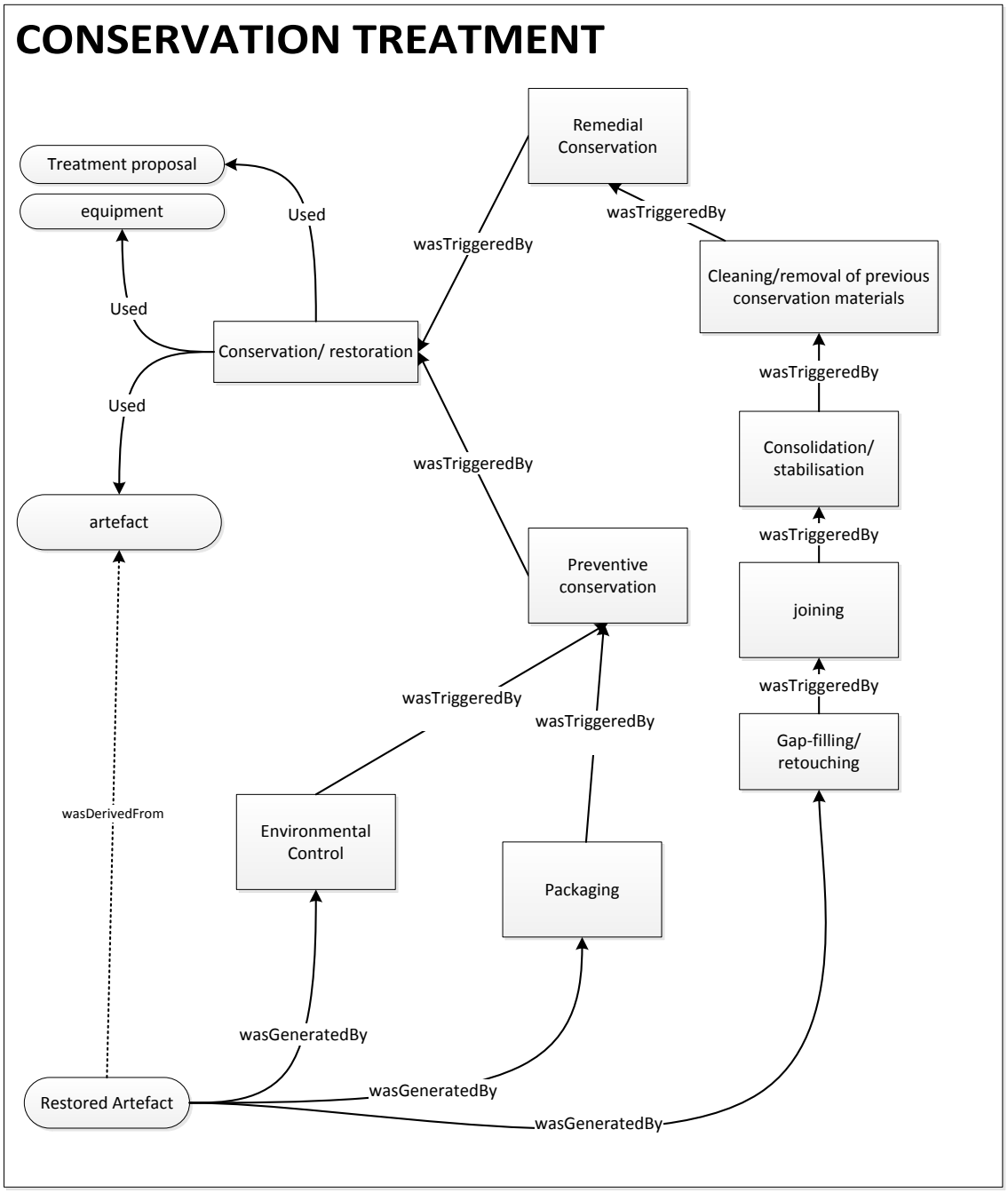
Graph 53: OPM Graph of artefacts' registration (Graph author's own).



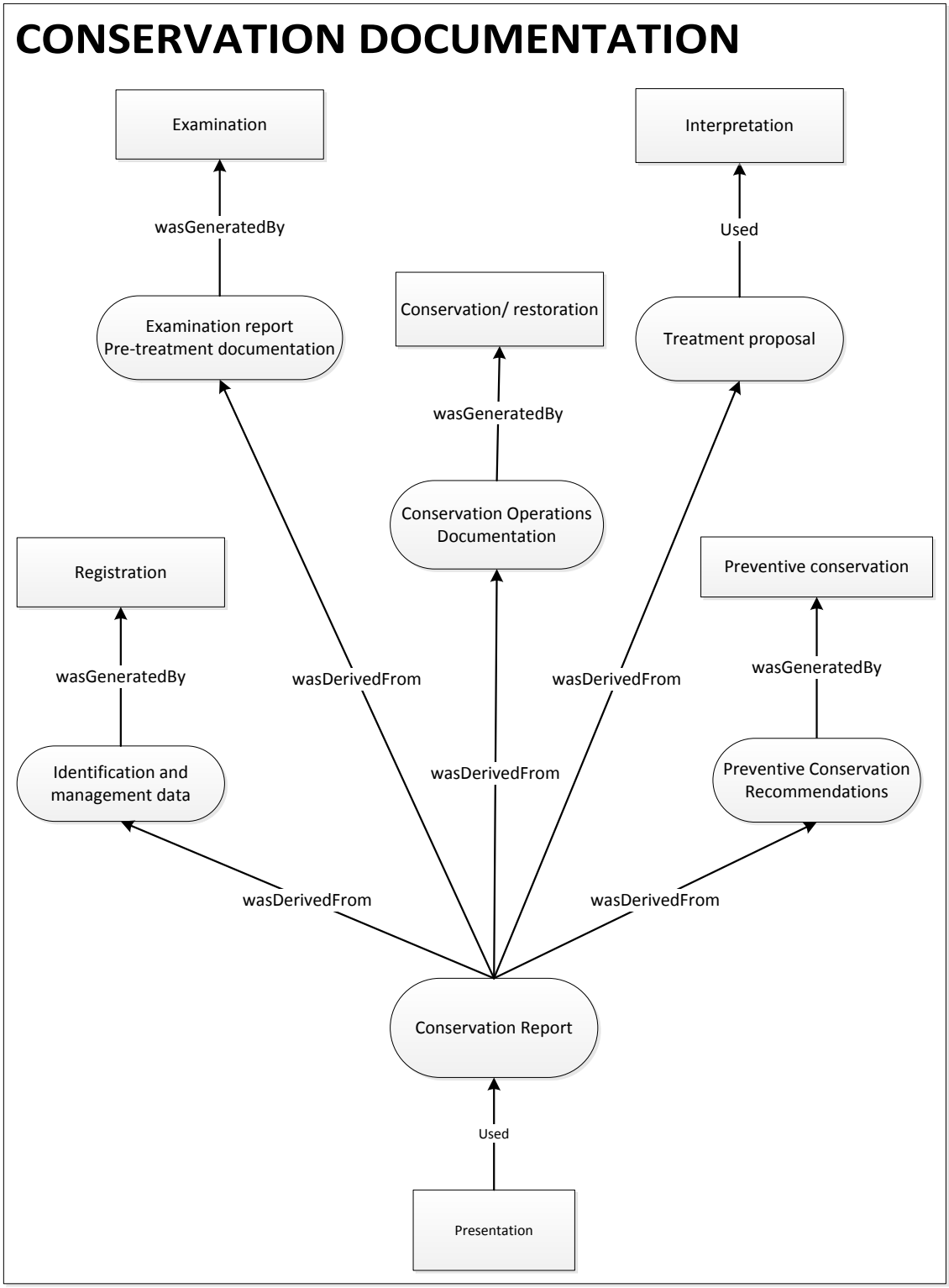
Graph 54: OPM Graph of examination (Graph author's own).



Graph 55: OPM Graph of conservation treatment proposal (Graph author's own).



Graph 56: OPM Graph of conservation treatment (Graph author's own).



Graph 57: OPM Graph of conservation documentation (Graph author's own).

A.2 Traditional documentation and recording strategies

Sketches, drawings, casts and film photographs and hand-written notes were among the most common means of documentation in the past. Those traditional approaches are still in use. For their critical justification one should take under consideration the expertise and time needed, as well as the quality-accuracy of the result, in addition to its possible uses in cultural heritage.

A.2.1 Sketches

There is no doubt that due to practical reasons sketches can easily, quickly and inexpensively help hold a record of a find, such as its dimensions and overall shape. Undoubtedly, this record is sufficient neither for dissemination nor for research purposes. Its value is restricted to communication and cooperation between the professionals on site or in the museum. Worth mentioning is that sketches retrieved from excavation diaries of past generations are considered important evidence and treated with respect, as archaeological evidence. Often this attitude is related to important archaeological sites or to masters of the field, whose contribution to archaeological research is unambiguous. Apart from the historical and research value of this action, sentimental factors also dictate such practices.

A.2.2 Drawings

Drawings, either simple or more stylistic ones, have been largely used in the past and are still in use for recording and dissemination of artefacts. These illustrations cannot be considered as a fast and quick method, because they are time-consuming and require special skills. Even experienced illustrators need a lot of time in order to finish a drawing of a complex artefact, like those usually found in excavation publications, along with its decoration and a possible section. The accuracy of such drawings remains under question, not only because they are dictated by the subjective judgement of the individuals who take part in the design process, in the most cases being the archaeologist and the illustrator, but also due to the inevitable human error in the perception of detail. Worth mentioning is that drawings can be useful for the recording and documentation of specific features, and consequently are preferred by a group of professionals in cultural heritage. They can communicate the basic characteristics of shape, decoration and condition easily. Drawings are

recommended also because they compel the illustrator, who in many cases is the archaeologist or the conservator, to devote enough time to the artefact. This detailed observation can assist in the characterization of the material and future choices of conservation, display or interpretation.

A.2.3 Photography

Film photography, along with various photographic techniques, served as a meaningful mean of documentation for many years, but nowadays it is substituted by digital imaging. Drawbacks of photography are the inefficiency in capturing fine details, usually recognised in close observation of the object, especially in cases of deteriorated, although decorated, artefacts. A characteristic example of misleading information delivered from photographs, highly important for conservation condition reporting, is the conjunctions between damages and alterations or decoration elements, such as engravings. It is difficult to capture accurately not only the colour and the shape but also the texture of the object in a single shot. So, professional equipment and expertise is needed. Nowadays, due to the advances in the field of digital imaging, the cost of such equipment is steadily decreasing, reaching affordable rates.

A.2.4 Casting

Casting is a method for recording and physical replication, useful in many cases because it can capture morphological information of the object. Its use is restricted to artefacts stable enough to undergo the necessary handling and pressure as well as contact with other materials. In cases of fragile artefacts this technique can cause irreversible damage. Understandably its use is not recommended, as it does not conform to contemporary museum standards.

Appendix B

B.1 Using replicas in conservation research

The process of replication archaeological material in order to examine specific research questions and provide answers to archaeological issues is rooted on experimental archaeology theory and practice, where the production, use, discard, deterioration, or recovery of material culture is being questioned (Ferguson, 2010). The concept of replication of archaeological material in conservation studies derive from the same objective to gain knowledge from the small non representative sample of artefacts already unearthed or explored. In such studies, researcher should decide whether to use authentic or surrogate objects, composed of art materials that resemble as much as possible the authentic raw materials used by our ancestors. This decision affects not only the character of the experiment but also its reliability. Each option has its advantages and drawbacks. There is no doubt that the experimentation with simulated objects provides flexibility and overcomes ethical considerations. The researcher is free to contact certain operations or manipulation, destructive and of deteriorative nature, not only at a minor sample of authentic material but on larger portions. It is well understood that such actions would have been considered unethical if applied to authentic material but they are totally acceptable for on purpose built testers-study units. On the contrary, the main disadvantage is that the success of the experimentation on surrogates does not necessarily mean that the method under examination would be successful if tested on real objects, because of the complexity of archaeological material. Owing to that, the results obtained from surrogates need verification with actual art objects (Reedy and Reedy, 1992).

From the above it becomes obvious that a compromise between authentic study units and surrogates is the most objective methodological approach according to experimental design principles because on purpose build testers enable better control over experimentation and simultaneously original materials provide the necessary verification, justifying methods and attributing extra value to the results.

The use of replicas and testers is fully reasonable for the purposes of the present research from an ethical perspective. Although the methodologies consist entirely of not destructive techniques, the initial application in replicas is an ethical and respectful approach towards original artefacts. Hence, unnecessary manipulation of authentic artefacts is avoided, minimising, in that way, the risks. Also, in practical terms this approach offers the opportunity for unlimited capture tests in a more controlled environment than the museum lab, and as a result provides the necessary data for the development of an improved diagnostic methodology. Considering museum policies, the limited time provided with access to the authentic artefacts, especially in case of the artefacts on display, as well as the geographical distribution of authentic artefacts used as case studies, the use of replicas is considered a valuable addition to the present research.

Appendix C

C.1 RTI case studies documentation

C.1.1 Paintings (replicas)

Table 33: Paintings (replicas) RTI case study documentation

	Object	Method	Lighting	Figures	Section
Painted wood panels	Icon 1, Jesus	H-RTI	visible	133-141	5.3.2.1.1
			IR-850nm		
	Icon 2 St John, St Proxoros		visible		
			IR-760nm		
			IR-950nm		
	Egyptian replica	Dome	Reflected visible	144, 145	5.3.2.1.1.1
			Reflected IR		
			FCIR		
Canvas testers	Tester 1- 2- 3	H-RTI	Reflected visible	146-152	5.3.2.1.2
	Tester 1- 2- 3		Reflected IR-760nm		
	Tester 3	Dome	Transmitted visible		
			Reflected visible		
			Reflected visible with transmitted lighting		
	Tester 1- 2- 3	H-RTI	Transmitted visible		
	Tester 1- 2- 3		Transmitted IR-850nm		
Canvas Paintings	Canvas 1 (girl) Frontside	H-RTI	Reflected visible	153-165	5.3.2.1.3
			Transmitted IR		
			Transmitted visible		
	Canvas 1 (girl)Backside		Transmitted IR		
			Transmitted visible		
	Canvas 2 Frontside		Transmitted visible		
			Reflected visible		
			Transmitted IR		
			Reflected IR		

C.1.2 Archaeological Materials

Table 34: Archaeological Materials RTI documentation (stone, glass, mortar and organics)

	Object		Method		Figures	Section
Stone	A84	Alabaster alabastron body	H-RTI	macroscopic	166-170	5.3.2.2.1
		Alabaster alabastron handles and small fragments	dome	microscopic		
	B61	Alabaster alabaston B61	H-RTI	normal		
Glass	D31-32	Core-formed alabastra of dark blue glass, decorated with dense feather pattern in white, blue and yellow	H-RTI	macroscopic	171-175	5.3.2.2.2
Mortar	Z41	wall painting fragments	H-RTI	visible	176-183	5.3.2.2.2
				IR-850nm		
	Z42			visible		
				IR-950nm		
				IR-760nm		
Ivory	E7	Incised ivory plaques fragment. Detail of Eros with remnants of colour decoration (blue and red)	H-RTI	macroscopic	226-229	5.3.2.2.5
	E8	Incised ivory plaques fragment. Detail of young male with remnants of red colour/ Detail of man's shoulder/ Detail of woman's clothing with remnants of red colour.	dome	microscopic		
Bone	A60	Wreath fragment. Bone stem.	H-RTI	microscopic		
Wood	A60	Wood fragment	H-RTI	microscopic	219	
	B101	Wood fragment from pyxis	H-RTI	macroscopic		
		Wood fragment from pyxis cup	dome	macroscopic		
Leather	B109	Leather fragment with textile imprints	dome	microscopic	220-225	
				macroscopic		
			H-RTI	macroscopic		
	B114	Leather fragment of a belt/strap	dome	microscopic		
		Leather fragment attached to a copper alloy ring	H-RTI	macroscopic		
	A21	Burnt leather fragment with holes at serial arrangement for sewing	H-RTI	macroscopic		
			dome	microscopic		

Table 35: Archaeological Materials RTI documentation (papyrus, silver, bronze and iron)

		Object	Method		Figures	Section
Papyrus		back side	H-RTI	Reflected visible	232-242	5.3.2.2.5
		front side	H-RTI			
		back side	H-RTI	trans-visible		
		front side	H-RTI	Reflected IR-720nm		
		front side	H-RTI	Reflected IR-850nm		
		front side	H-RTI	Reflected IR-950nm		
		back side of the mount	H-RTI	trans-IR-850nm		
Silver	A19	Gold gilded silver sheet in the shape of shield with repousse scene of a Macedonian shield	dome	microscopic	250-252	5.3.2.2.6
			dome	macroscopic		
			H-RTI	microscopic		
Bronze	A60	Wreath fragment. Gold gilded bronze leaf	dome	macroscopic	243-246	
		Wreath fragment. Bronze stem	dome	macroscopic		
	C4	Bronze coin- non identified	H-RTI	macroscopic		
		Bronze coin- non identified	dome	macroscopic		
		Bronze coin- non identified	dome	microscopic		
	Z13	Bronze embossed head of a woman	H-RTI	macroscopic		
	Z32	Fragment of bronze mirror	H-RTI	macroscopic		
		Fragment of bronze mirror	H-RTI	microscopic		
		Fragment of bronze mirror	H-RTI	normal		
		Wall painting fragment	H-RTI	normal		
	A60	Wreath fragment. Gold gilded bronze leaf	dome	microscopic		
Iron	D52	Spear handle. Corroded with wood inside	H-RTI	normal	247-249	
	B118	Board fragment/Corner fragment/ Double corner fragment.	H-RTI	normal		
	B106	Knife. Part of the bone handle and the iron blade.	H-RTI	macroscopic		
		Knife. Part of the bone handle and the iron blade.	H-RTI	normal		

Table 36: Archaeological Materials RTI documentation (ceramics)

	Object	Method		Figures	Section
Ceramics	A99 Ceramic roundel with the head of Athena Parthenos	H-RTI	Normal visible		5.3.2.2.4
		dome	macroscopic visible		
		dome	Microscopic visible		
		H-RTI	microscopic visible		
	C3 th (II) Fragments of a canthar - cylix with a heart-shaped leaf pattern	H-RTI	macroscopic visible	185-187	
		dome	microscopic visible		
	C3e Fragments of a skyphos	H-RTI	macroscopic visible		
		dome	microscopic visible		
	C1 Red figure pelike. Horse scene.	H-RTI	visible	188-193 & 195-196	
			IR-950nm		
	C1 Red figure pelike. Female figure with tiara		visible		
			IR-850nm		
	H2 Red figure pelike. Aphrodite, seated, looking left at Eros.		IR-720nm		
			visible		
			IR-760nm		
			IR-850nm		
			IR-950nm		
			visible		
			IR		
	H2 Red figure pelike. Decorative motif.		IR-950nm		
	Z29 Ceramic skyphos, blackglazed.		visible	184	
	GN Gnathian skyphos frontside		visible	197-206	
			IR-950nm		
			Reflected UV		
			UV induced visible fluorescence		
	GN Gnathian skyphos backside		visible		
			IR-950nm		
			Reflected UV		
			UV induced visible fluorescence		
	367 Faenza maiolica fragment		visible IR-850 Reflected UV	207-214	
	367 Faenza maiolica fragment		visible IR-850		
	366 Faenza maiolica fragment 1 & 2		visible		
			IR-850		

C.1.3 Numismatics RTI case study documentation

Table 37: Numismatics RTI case study documentation

Coin no	Material	Diam. mm.	RTI Visualization				method	Section / Figures
			obv/ rvs	Conservation state				
				before	during	after		
1	copper	17	obv			✓	H-RTI	5.3.2.3 253-266 and 271-276
			rvs			✓	H-RTI	
2	copper	16	obv			✓	H-RTI	
			rvs			✓	H-RTI	
3	copper	16	obv			✓	H-RTI	
			rvs			✓	H-RTI	
4	copper	17	obv	✓	✓	✓	MINI-DOME1	
5	copper	17	obv	✓	✓	✓	MINI-DOME1	
			rvs	✓	✓	✓	MINI-DOME1	
6	copper	18	obv	✓		✓	MINI-DOME1	
			rvs	✓		✓	MINI-DOME1	
7	copper	15	obv	✓		✓	MINI-DOME1	
8	copper	13	obv			✓	MINIDOME1	
			rvs			✓	MINI-DOME1	
9	copper	12	obv			✓	MINI-DOME1	
			rvs			✓	MINI-DOME1	
10	copper	16	obv			✓	MINI-DOME1	
			rvs			✓	MINI-DOME1	
12	copper	18	obv			✓	MINI-DOME1	
			rvs			✓	MINI-DOME1	
13	silver	10	obv	✓			MINI-DOME1	
			rvs	✓			MINI-DOME1	
14	silver	8	obv	✓			MINI-DOME1	
			rvs	✓			MINI-DOME1	
15	silver	8	obv	✓			MINI-DOME1	
			rvs	✓			MINI-DOME1	
16	silver	9	obv	✓			MINI-DOME1	
			rvs	✓			MINI-DOME1	
17	silver	9	obv	✓			MINI-DOME1	
			rvs	✓			MINI-DOME1	
18	copper	23	obv	✓		✓	MINI-DOME2	
			rvs	✓		✓	MINI-DOME2	
19	copper	23	obv	✓			MINI-DOME2	
			rvs	✓			MINI-DOME2	
20	silver	19	rvs			✓	MINI-DOME2	
21	silver	17	obv			✓	MINI-DOME2	
22	copper	22	rvs	✓		✓	MINI-DOME2 & H-RTI	
23	copper	26	obv	✓			MINI-DOME2	
			Rvs	✓		✓	MINI-DOME2 & H-RTI	
24	copper	20	rvs	✓			H-RTI	
25	copper	26	rvs	✓			MINI-DOME2	
D2	gold	10	obv			✓	MINI-DOME1	
			rvs			✓	MINI-DOME1	

C.2 PG case studies documentation

Table 38: PG case studies documentation (paintings and archaeological materials)

	Object		Method	Figures	Section
Paintings	Tester 3		visible	309-317	5.4.2.1.
			IR-850		
			Transmitted visible		
			Transmitted infrared		
			Microscopic detail		
Archaeological materials	**Ceramic**	Neopunic amphora AM	Visible	318-326	5.4.2.2.1
		Black-glazed chous BGC			
		Gnathian chous GNC			
		Geometric kantharos KA	Visible		
			IR-850		
		Gnathian kylix GNK	Visible		
		Gnathian skyphos GNS			
	stone	Drum 2 D2		331-334	5.4.2.2.4
		Drum3 D3			
	Textile	Fragment			5.4.2.2.5
	Metal	Iron sundial SUN		327-330	5.4.2.2.3
		Silver coin CO			
		Bronze Oinochoe handle OH			
		Bronze Patera handle PT			

C.3 Manual Fragments matching case study documentation

A name was assigned to each fragment as shown in the Figure 432.

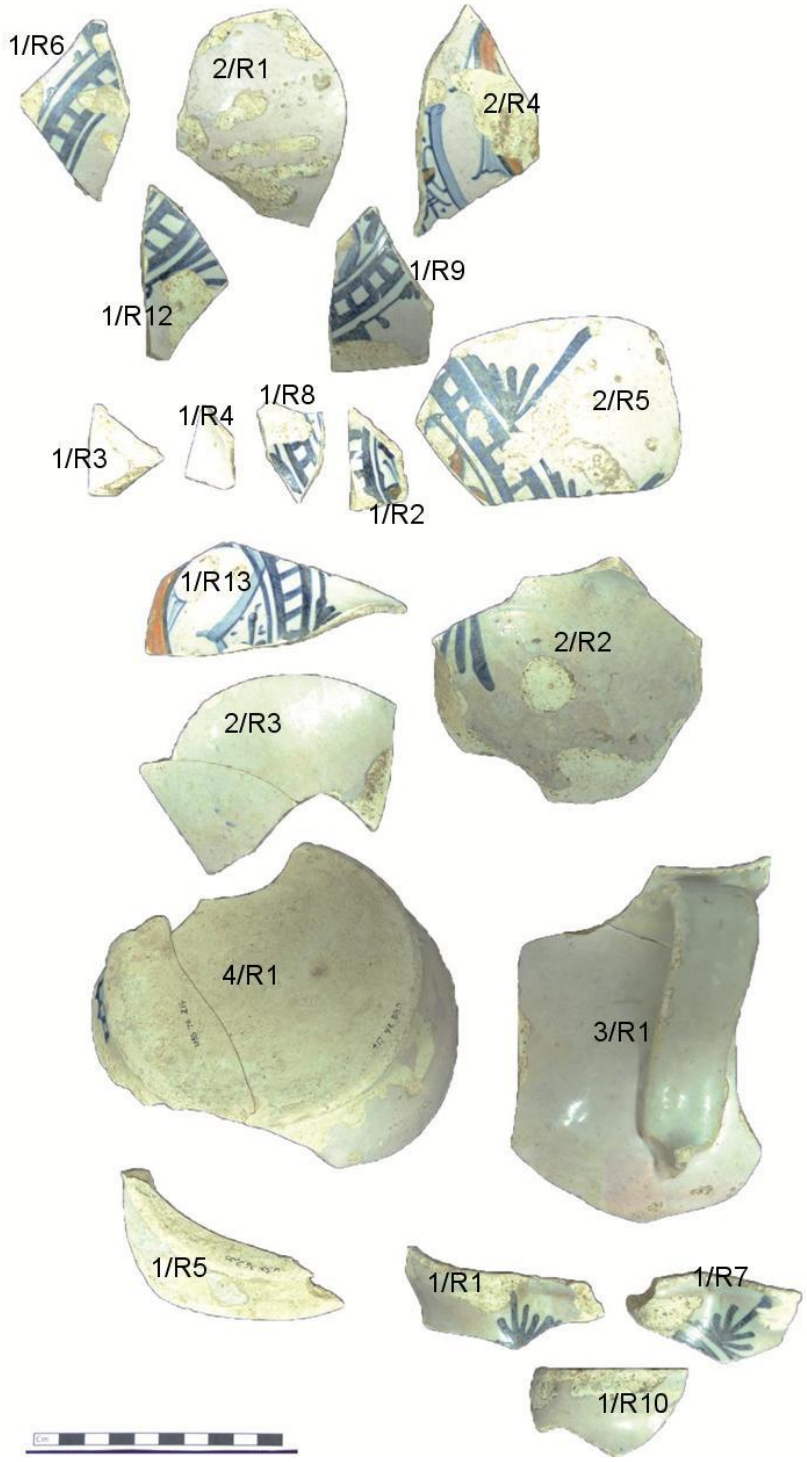


Figure 432: Names assigned to the digitised fragments of jug No 366

The process of manual fragments matching was video recorded. Video files are available in the digital library, along with transcripts. The Table 39 shows the transcripts from the video files, including timestamps and the actions that took place.

In general, the following actions were executed:

- Matching the two fragments of the base, 4/R1 and 1/R5 (Group A)
- Matching fragments 1/R12 and 1/R13 (Group B)
- Matching Group B with fragments 2/R4, 1/R6 and 1/R9 (Group C)
- Matching fragments 1/R2 and 1/R8 (Group D)
- Matching Groups C and D (Group E)
- Matching fragments 1/R7 and 1/R10 (Group F)
- Matching Groups E and F (Group G)
- Matching Groups G and 1/R1 (Group H)
- Matching fragments 2/R3 and 3/R1 (Group I)
- Matching Groups I and 2/R5 (Group J)
- Matching Groups H and J (Group K)
- Matching fragments 2/R1 and 1/R3 (Group L)
- Matching Groups K and L (Group M)
- Matching Groups M and A (Group N)

Table 39: Transcripts from the video files

Video file	Time-stamp	ACTIONS	FRAGMENT	FRAGMENT
Group_A.mov	00:00	OBSERVATION		
Group_A.mov	00:07	SELECTING	4/R1	
Group_A.mov	00:12	SELECTING	1/R5	
Group_A.mov	00:19	TESTING	4/R1	1/R5
Group_A.mov	00:25	MATCHING	4/R1	1/R5
Group_A.mov	00:27	SECURING	4/R1	1/R5
Group_B.mov	00:03	OBSERVATION		
Group_B.mov	00:09	SELECTING	2/R4, 1/R6 AND 1/R9	
Group_B.mov	00:13	SELECTING	1/R2	
Group_B.mov	00:16	SELECTING	1/R12	
Group_B.mov	00:18	SELECTING	1/R8	
Group_B.mov	00:21	SELECTING	1/R13	
Group_B.mov	00:29	TESTING	2/R4, 1/R6 AND 1/R9	1/R12

Group_B.mov	00:46	TESTING	2/R4, 1/R6 AND 1/R9	1/R13
Group_B.mov	01:06	TESTING	1/R12	1/R13
Group_B.mov	01:21	MATCHING	1/R12	1/R13
Group_B.mov	01:30	SECURING	1/R12	1/R13
Group_C.mov	00:01	TESTING	2/R4, 1/R6 AND 1/R9	1/R12+1/R13
Group_C.mov	00:16	MATCHING	2/R4, 1/R6 AND 1/R9	1/R12+1/R13
Group_C.mov	00:31	SECURING	2/R4, 1/R6 AND 1/R9	1/R12+1/R13
Group_D.mov	00:00	OBSERVATION		
Group_D.mov	00:12	SELECTING	2/R5	
Group_D.mov	00:14	TESTING	1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R5
Group_D.mov	00:45	TESTING	1/R2	1/R8
Group_D.mov	00:59	MATCHING	1/R2	1/R8
Group_D.mov	01:24	SECURING	1/R2	1/R8
Group_E.mov	00:00	TESTING	1/R2+1/R8	1/R12+1/R13+2/R4, 1/R6 AND 1/R9
Group_E.mov	00:02	MATCHING	1/R2+1/R8	1/R12+1/R13+2/R4, 1/R6 AND 1/R9
Group_E.mov	00:09	SECURING	1/R2+1/R8	1/R12+1/R13+2/R4, 1/R6 AND 1/R9
Group_F.mov	00:00	SELECTING	1/R10	
Group_F.mov	00:10	SELECTING	1/R7	
Group_F.mov	00:12	TESTING	1/R7	1/R10
Group_F.mov	00:19	SELECTING	1/R1	
Group_F.mov	00:26	TESTING	1/R10	1/R1
Group_F.mov	00:34	TESTING	1/R1	1/R7
Group_F.mov	00:49	TESTING	1/R10	1/R7
Group_F.mov	00:59	MATCHING	1/R10	1/R7
Group_F.mov	01:11	TESTING	1/R10+1/R7	1/R1
Group_G.mov	00:00	TESTING	1/R10+1/R7	1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9
Group_G.mov	00:06	MATCHING	1/R10+1/R7	1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9

Group_H.mov	00:06	TESTING	1/R10+1/R7	1/R1
Group_H.mov	00:09	MATCHING	1/R10+1/R7	1/R1
Group_H.mov	00:25	SECURING		
Group_H.mov	01:02	TESTING	1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9+1/R1	1/R4
Group_H.mov	01:05	SECURING		
Group_I.mov	00:07	TESTING	1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R5
Group_I.mov	00:14	MATCHING		
Group_I.mov	00:33	TESTING	2/R5	2/R2
Group_I.mov	00:40	TESTING	2/R2	2/R3
Group_I.mov	00:56	TESTING	2/R2	2/R1
Group_I.mov	01:03	TESTING	2/R1	2/R2
Group_I.mov	01:36	TESTING	2/R3	2/R2
Group_I.mov	02:28	TESTING	2/R1	2/R3
Group_I.mov	02:34	TESTING	2/R1	2/R2
Group_I.mov	02:42	SELECTING	3/R1	
Group_I.mov	02:44	TESTING	3/R1	2/R1
Group_I.mov	02:52	TESTING	3/R1	2/R3
Group_I.mov	03:09	TESTING	3/R1+2/R3	2/R1
Group_I.mov	03:29	SECURING	3/R1	2/R3
Group_I.mov	03:53	TESTING	3/R1+2/R3	2/R2
Group_K.mov	00:06	TESTING	3/R1+2/R3+2/R5	1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9
Group_K.mov	00:39	SECURING		
Group_L-M.mov	00:00	TESTING	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	1/R3
Group_L-M.mov	00:15	TESTING	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R1

Group_L-M.mov	00:39	TESTING	2/R2	2/R1
Group_L-M.mov	00:47	TESTING	2/R1	1/R3
Group_L-M.mov	00:57	SECURING	2/R1	1/R3
Group_L-M.mov	01:30	TESTING	2/R1+1/R3	2/R2
Group_L-M.mov	01:58	TESTING	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R1+1/R3
Tests_2-R2.mov	00:00	TESTING	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9+2/R1+1/R3	2/R2
Group_N.mov	00:23	TESTING	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9+2/R1+1/R3	4R1+1/R5

Table 40: Transcript from the video files, for testing joins

Video file	Time-stamp	FRAGMENT	FRAGMENT	UNSUCCESSFUL TESTS	SUCCESSFUL TESTS	CRITERION
Group_A.mov	00:19	4/R1	1/R5		1	Shape
Group_B.mov	00:29	2/R4, 1/R6 AND 1/R9	1/R12	6		Painted design
Group_B.mov	00:46	2/R4, 1/R6 AND 1/R9	1/R13	4		Painted design
Group_B.mov	01:06	1/R12	1/R13	1	1	Painted design
Group_C.mov	00:01	2/R4, 1/R6 AND 1/R9	1/R12+1/R13	2	1	Painted design
Group_D.mov	00:14	1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R5	8		Painted design
Group_D.mov	00:45	1/R2	1/R8	5	1	Texture and shape
Group_E.mov	00:00	1/R2+1/R8	1/R12+1/R13+2/R4, 1/R6 AND 1/R9		1	Shape
Group_F.mov	00:12	1/R7	1/R10	2		Shape
Group_F.mov	00:26	1/R10	1/R1	1		Shape
Group_F.mov	00:34	1/R1	1/R7	1		Shape
Group_F.mov	00:49	1/R10	1/R7		1	Shape
Group_F.mov	01:11	1/R10+1/R7	1/R1	2		Shape
Group_G.mov	00:00	1/R10+1/R7	1/R2+1/R8+1/R12+1/R13+2	2	1	Shape

			/R4, 1/R6 AND 1/R9			
Group_H.mov	00:06	1/R10+1/R7	1/R1		1	Shape
Group_H.mov	01:02	1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9+1/R1	1/R4		1	Shape
Group_I.mov	00:07	1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R5	1	1	Painted design
Group_I.mov	00:33	2/R5	2/R2	3		Shape
Group_I.mov	00:40	2/R2	2/R3	2		Texture
Group_I.mov	00:56	2/R2	2/R1	1		Texture
Group_I.mov	01:03	2/R1	2/R2	3		Texture
Group_I.mov	01:36	2/R3	2/R2	1		Shape
Group_I.mov	02:28	2/R1	2/R3	1		Texture
Group_I.mov	02:34	2/R1	2/R2	1		Texture
Group_I.mov	02:44	3/R1	2/R1	2		Texture
Group_I.mov	02:52	3/R1	2/R3	2	1	Texture and shape
Group_I.mov	03:09	3/R1+2/R3	2/R1	3		Texture and shape
Group_I.mov	03:53	3/R1+2/R3	2/R2	2		Texture and shape
Group_K.mov	00:06	3/R1+2/R3+2/R5	1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9		1	Shape
Group_L-M.mov	00:00	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	1/R3	5		Shape
Group_L-M.mov	00:15	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R1	5		Shape
Group_L-M.mov	00:39	2/R2	2/R1	3		Texture
Group_L-M.mov	00:47	2/R1	1/R3	1	1	Texture
Group_L-M.mov	01:30	2/R1+1/R3	2/R2	1		Texture
Group_L-M.mov	01:58	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9	2/R1+1/R3	1	1	Shape

Tests_2-R2.mov	00:00	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9+2/R1+1/R3	2/R2	5		Texture and shape
Group_N.mov	00:23	3/R1+2/R3+2/R5+1/R10+1/R7+1/R2+1/R8+1/R12+1/R13+2/R4, 1/R6 AND 1/R9+2/R1+1/R3	4R1+1/R5		1	Shape

C.4 Replacement of lost material documentation

File: HMS_UK_COP_PATERA.max

C.4.1 Geometry

Objects in the scene:

- PATERA-BASE
- PATERA-TERMINAL
- PATERA-HANDLE
- Handle-replacement
- Body-replacement
- Stand

Cameras:

- Camera001
- Camera002
- Camera003
- Camera004

Lights:

- PhotometricLight001
- PhotometricLight002
- PhotometricLight003
- PhotometricLight004

Scene Totals:

- Objects: 10
- Cameras: 4
- Lights: 4
- Total: 18

Mesh Totals:

- Verts: 1022290
- Faces: 1768576

C.4.2 Materials

The following materials were used:

- Stand: simple grey
- Plexiglas: Arch& Design material, translucent with light grey colour
- Simple-colour (colour-a): greenish colour
- Variation of simple colour with a cellular map
- Variation of simple colour material with a diffuse colour map
- Body material, based on simple colour with a smoke diffuse colour map

The 3ds Max file HMS_UK_COP_PATERA.max is included in the digital library.

Appendix D

D.1 Guidelines for the digital library

A representative sample of the data was selected for the Digital Library, because it would have been impossible to include the whole dataset captured and processed for the purposes of the present research. The Digital Library is submitted as accompanying material for the thesis. Renderings, graphs and screenshots included in the main chapters of this thesis demonstrate the methodology, materials and techniques used as well as the findings of this research.

D.1.1 Structure

The digital files are organised in folders (**'section5.3'**, **'section5.4'**, **'section6.2'**, **'section6.3'**, **'section6.4'**) by subject following the structure of the thesis.

D.1.2 Contents

The folder **'section5.3'** contains 8 polynomial texture maps (.ptm) and 64 reflectance transformation images (.rti). The folder **'section5.4'** contains 23 agisoft photoscan files (.psz). The folder **'section6.2'** includes the following folders:

- SCC_UK_CER_FM366_Manual, which contains 13 video files (.mov) and 1 excel file (.xlsx)
- SCC_UK_CER_FM366_Semiautomatic, which contains 1 file in object file format (.obj)
- SCC_UK_CER_FM366-DigitisedFragments, which contains 19 files in object file format (.obj)
- SCC_UK_CER_FM367-DigitisedFragments, which contains 28 files in object file format (.obj)
- SCC_UK_CER_FM367_Semiautomatic, which contains 5 files in alignment file format (.aln) and 5 files in object file format (.obj), plus 37 auxiliary files in .obj and .ply format
- SCC_UK_CER_FM367_Semiautomatic_Final, which contains 1 file in object file format (.obj)

The folder **'section6.3'** contains 1 3ds Max file (.max) and 1 image file (.jpg) and the folder 'HMS_UK_COP_PATERA_DigitisedFragments'. The latter contains 3 files in object file format (.obj), 3 material files (.mtl) and 22 image files

(.jpg). The folder **'section6.4'** contains 2 3ds Max file (.max), 2 reflectance transformation images (.rti).

The four folders of the digital library contain 244 files. The total size of the Digital Library is 11 GB. The following list summarizes the size of the individual folders:

- section5.3 4.75 GB
- section5.4 2.11 GB
- section6.2 3.80 GB
- Section6.3 0.29 GB
- Section6.4 0.14 GB

D.1.3 File formats and compatible software

The Digital Library includes files in .pdf, .mov, .jpg, .png compatible with a broad range of commonly used software. In addition there are:

- Polynomial texture maps (.ptm) and reflectance transformation images (.rti) are compatible with the RTIViewer software available for free from Cultural Heritage Imaging
- Agisoft photoscan files (.psz) can be viewed in Agisoft photoscan (commercial software). Nevertheless, the reconstructed models of the artefacts were exported in so as to be compatible with free software (for example Mesh Lab)
- Files in alignment file format (.aln) and in object file format (.obj) are compatible with Mesh Lab
- Material file (.mtl) and 3ds Max file (.max) can be viewed in 3ds max.

D.1.4 Naming convention

Table 41: Naming convention

Collections/Provenance			
Archaeological Museum of Thessaloniki		**AMTH-GR**	
Archaeological Museum of Amphipolis		**AMA-GR**	
Hampshire County Council Museums Service		**HMS-UK**	
Southampton City Council, Arts &Heritage		**SCC-UK**	
University of Southampton, Archaeological Collections		**USOU-UK**	
The British Museum		**BM-UK**	
Private collection/replica		**REP**	
Material code			
Ceramic	**CER**	Papyrus	**PAP**
Glass	**GL**	Ivory	**IVO**
Copper	**COP**	Leather	**LEA**
Silver	**SIL**	Wood	**WOO**
Gold	**GOL**	Mortars	**MOR**
Iron	**IRO**	Composite	**COM**
Alabaster	**ALA**	Painted canvas	**PCAN**
Sandstone	**SAN**	Painted wood panel	**PWOO**
RTI visualization method code			
Macroscopic		**MA**	
Microscopic		**MI**	
H-RTI		**H**	
MINIDOME1		**MD1**	
MINIDOME2		**MD2**	
Visible		**VIS**	
Infrared (followed by an indication of the filter used in nm) e.g. IR-850		**IR**	
Reflected UV		**UVR**	
UV induced visible fluorescence		**UVF**	
transmitted		**T**	
desaturated		**BW**	
Conservation State codes			
Before conservation		**BC**	
After conservation		**AC**	
During conservation		**DC**	

Each visualization is named as follows:

Collection/Provenance_Material code_Object code (a,b,c)_RTI visualization method code. file type extension

For the numismatic case study each visualization is named as follows:

Collection/Provenance_Material code_Object code_obv/rvs_Conservation state code__RTI visualization method code.rti or ptm

Example for RTI file: **AMTH-GR_GOL_D2_obv_AC_VIS-MI-MD1.rti**

Microscopic RTI visualization of the obverse of gold coin from the collection of the Archaeological Museum of Thessaloniki, with assertion number D2, visualised in the visible spectral area after conservation with minidome 1.

Example for 3d model: **BM_UK_SAN_D2.obj**

3d model in OBJ format of object Drum 2 made of sandstone from the collection of the British Museum.

Appendix E

E.1 Design for a micro dome

E.1.1 Minimum requirements

- *Portable*: The dome should be capable of capturing data in different settings (imaging labs, museums' labs). All the main components of the data capture system should be included in one portable device so as to avoid problems of compatibility with different microscopic facilities available in different labs.
- *Safe:* The dome should minimise human-object-device interaction, and provide easier positioning of the sample.
- *Automatic/ Easy to use*: The dome should enable quick data capture and eliminate manual handling of the device to ensure high quality datasets, even when users are not familiar with RTI technique.
- *Flexible:* Need to capture data in different magnification (fragments or samples taken from objects or details of larger objects)

E.1.2 Main components and additional features

The main components are the USB Microscope (for example AM4815ZT Dino-Lite Edge), the auxiliary data capture device-dome, a stand and a connector. The dome, with a diameter circa 13cm., is equipped with 128 tiny LEDs (1mm-3mm) with adjustable brightness connected to a LED driver. The LEDs are positioned in 16 axes from 8 different angles (circa 65-70^0 max angle, 15^0 min angle). The stand functionality should be similar to the, able to turn 3600 flex-arm type, so as to capture any detail, even in case of large objects that cannot be placed on a table (a large pot, a wall painting, a statue). The model MS52BA2 of dinolite fulfils these requirements. The connector ensures safe attachment of the dome to the microscope and to enable the movement of the microscope closer or further away from the sample, so as to achieve the optimum distance between the microscope and the sample (max. 6cm, min 1cm) and capture in different magnifications from x20, a little bit less than 2 cm (ideal for coins, archaeological samples, small fragments) up to x220 (ideal for tiny details-less than 1, 5 - 1,8mm).

Proposals for better functionality are the following:

- Light pad
- WiFi Streamer
- IR-LEDs + IR USB Microscope

E.1.3 Workflow for data capture

Step 1: preparations

- Place the artefact on the correct position, adjust the magnification and check that all the settings in the specialised software that comes with the microscope (open source software) are correct (for example: turned off the microscope lights).
- Adjust the dome to the microscope stand. Make sure that you have the correct working distance to the object. Turn on your mini dome.

Step 3: lighting selection & data capture

A dialog box appears and asks you which operation you want to follow based on which settings you have chosen in step 1, the low (Option 1) or high magnification (Option 2). Then user should adjust the LED driver to the best brightness. The lights flash successively the images are captured (time-lapse image capture).

E.2 Recommendations for a virtual collaborative RTI environment

Each contributor should provide affiliation and link to a personal web-page (for example institutional or academia profile). Contributions takje the form of annotations, used in order to define, explain and characterise areas of the RTI image. The annotation includes creator's name (text and link), date, keywords, text, and reference commends. Three main types of annotations are suggested:

- uncertainty (?) Annotations with question mark used in case of an interpretation which is not supported with necessary evidence. This works also as an open question, topic for further discussion.

- Agree annotation (!) An annotation used to describe approval of a comment. It can be accompanied optionally by an explanation text, so as to provide an insight, into the issue discussed
- Disagree annotation (X). An annotation used to describe diaproval of a comment. It should be accompanied by an explanation text and provide alternative interpretation.

Contributions can also be accompanied by references commends (R), either internal cross-linking to another RTI image of the repository or external (a link to an online resource, book etc.).

In the virtual collaborative environment options for listing, searching/filtering, sorting annotations and as a keywords/references list should be available. For example:

- Sorting annotations: Annotations to be sorted according to author, date etc. If the user selects a specific area of the image the existing annotations of this area appear
- Keywords: a list of all the keywords used in annotations to appear so as for the users to locate the info they are interested easily.
- References: a list of all the references used in annotations to appear so as for the user to have a handy bibliography for the issues discussed in the annotations
- Contributors: a list of all the people who created annotations.

Appendix F

F.1 Project Metadata

Project Title	VIRTUALIZING CONSERVATION: EXPLORING AND DEVELOPING NOVEL DIGITAL VISUALIZATIONS FOR PREVENTIVE AND REMEDIAL CONSERVATION OF ARTEFACTS
Description	Development and application of computational imaging, computer vision and digitization techniques for enhanced examination and visual analysis. Graphical 3d modelling and physical 3d reproduction for interventive treatment. Workflows for digital and conventional conservation documentation
Subject	Conservation, restoration, digitization, imaging, virtual reconstruction
Coverage/ Spatial	Greece, Thessaloniki and Amphipolis United Kingdom, Hampshire, Southampton and Winchester
Coverage/Temporal	Neolithic, Classical-Hellenistic, Roman, Medieval, Modern
Creators	Eleni Kotoula
Contributors	University of Southampton Archaeological Museum of Thessaloniki Archaeological Museum of Amphipolis Hampshire County Council Museums Service Southampton City Council, Arts &Heritage The British Museum
Dates	2010-2014
Type	Thesis for the degree of Doctor of Philosophy
Format	.pdf, .rti, .ptm, , .obj, .psz, .aln, .max, .mtl, .jpg,.mov