ADDITIVE ARCHAEOLOGY: THE SPIRIT OF VIRTUAL ARCHAEOLOGY REPRINTED

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Περίληψη/ Abstract

Τη δεκαετία του 1980, οι αρχαιολόγοι υιοθετούσαν με θέρμη τα ραγδαία αναπτυσσόμενα πεδία της μοντελοποίησης μέσω υπολογιστών, των υπερκειμένων και της οπτικοποίησης ως οχήματα για την εξερεύνηση των αρχαιολογικών δεδομένων. Μπροστά στις νέες αυτές συνθήκες επινοήθηκε ο όρος ‘εικονική αρχαιολογία’. Ο όρος αρχικά προοριζόταν για να περιγράψει μια πολυδιάστατη προσέγγιση για τη μοντελοποίηση των φυσικών κατασκευών και των διαδικασιών της αρχαιολογίας του πεδίου, μέσω της οποίας η τεχνολογία θα μπορούσε να αξιοποιηθεί έτσι ώστε να επιτύχει νέους τρόπους εμπειρίας, καταγραφής και ερμηνείας των πρωτογενών αρχαιολογικών δεδομένων και διαδικασιών. Παρά τις αρχικές εκτιμήσεις ότι η ‘εικονική αρχαιολογία’ θα μπορούσε να επιφέρει τις προσδοκώμενες αλλαγές στην έρευνα πεδίου, εντούτοις δεν τα κατάφερε. Καθώς πλέον το αρχαιολογικό υλικό είναι κυρίως ψηφιακό, οι τομές, οι κατόψεις, τα σχέδια και οι φωτογραφίες αποτελούν αναπαραγωγή των αναλογικών μεθόδων που προηγήθηκαν. Η διατήρηση των συμβάσεων των αναλογικών μεθόδων καθίσταται ολοένα και περισσότερο αναχρονιστική με την επικράτηση των ψηφιακών τεχνολογιών και κυρίως με τις εξελίξεις του 21^{ου} αιώνα στο πεδίο της ‘προσθετικής κατασκευής’, που διαδόθηκε χάρη στους τρισδιάστατους εκτυπωτές, και δύναται να φέρει τον κόσμο της εικονικής αρχαιολογίας πιο κοντά με την υλικότητα της παραδοσιακής αρχαιολογίας. Το άρθρο αυτό υποδεικνύει πως παρά τις τεχνολογικές εξελίξεις, μεγάλο μέρος της θεωρητικής υποδομής στην οποία στηρίζεται η εικονική αρχαιολογία παραμένει επίκαιρο, τρεις και πλέον δεκαετίες μετά την αρχική χρήση του όρου. Μέσα από την ανάλυση των ταχέως αναπτυσσόμενων τεχνολογιών προσθετικής κατασκευής, το παρόν άρθρο θα δείξει πως είναι αναγκαίο να προχωρήσουμε πέρα από μια παθητική προσπάθεια προσαρμογής των τεχνολογιών με σκοπό να αναπτύξουμε αυθεντικές αρχαιολογικές προσεγγίσεις στην τεχνολογία.

Archaeologists in the 1980s were embracing wholeheartedly the rapidly expanding field of computer modelling, hypertext and visualisation as vehicles for data exploration. Against this backdrop ‘virtual archaeology’ was conceived. The term was originally intended to describe a multi-dimensional approach to the modelling of the physical structures and processes of field archaeology. It described some ways in which technology could be harnessed in order to achieve new ways of experiencing, documenting, interpreting and annotating primary archaeological materials and processes. Despite its initial promise, virtual archaeology failed to have the impact upon archaeological fieldwork which might have been expected. While the archaeological record is now primarily digital, its sections, plans, drawings and photographs are facsimiles of the analogue technologies which preceded them. This retention of analogue conventions is increasingly out of step with the general prevalence of digital technologies and especially 21st century advances in 'additive manufacturing', popularised through 3D printers, which could bring the world of virtual archaeology into closer alignment with the material one. This paper will set out to demonstrate that in spite of technological developments much of the theoretical infrastructure which underpinned virtual archaeology remains as relevant today as it was when the term was first conceived. Through an analysis of rapidly developing additive manufacturing technology, this paper will demonstrate the need to move beyond passive technological appropriation and towards the development of authentically archaeological approaches to technology.

Keywords: virtual archaeology, additive manufacturing, 3D printing, grand challenge

Introduction

Field archaeology, specifically excavations, to some people might seem, not without reason, to represent some kind of externalisation of an anarchic, destructive, drive in the archaeological psyche. Excavators in creating one kind of archaeological record effectively devours, and efficiently effaces, the original, ‘proper’, archaeological traces or residues from which the record is censored, and an archive created. Following Jacques Derrida (1996), this then becomes the place where things begin, the new starting point, the nexus of a new reality, where impressions collected while 'digging' become reality, embedded in the self-replicating topology of the archive. Many other potential realities become lost in a fog of institutionally induced amnesia, where all the selections and decisions by the diggers, supervisors and specialists that brought the excavation directors or report writers to this point along the path are largely forgotten, with other voices being muted, and nuanced narratives deflected into the margins.

1. The Origins of Virtual Archaeology

Four principal factors lead to the conception of virtual archaeology in 1990 (Fig. 1). The initial factor was the *Rescue* and *Salvage* archaeology lobbies in UK and North America which over the previous decades had successfully built a *polluter pays* platform by positioning archaeological remains as priceless, irreplaceable resources under threat. Public outcry about the treatment of several high profile archaeological remains had helped precipitate PPG 16 in the UK. Henceforth, developers in England and Wales were held responsible for determining the archaeological impact of development and to provide mitigation, or protection (McGill 1995). If the remains could not be preserved *in situ,* a fastidious, empiricist archaeology, couched in the trappings of positivist science, afforded the solution known as 'preservation by record'; in fact a set of *pre-structured* archives (Reilly 1992, 163, 170) Archaeology, however, particularly fieldwork, and especially excavation, is a craft discipline. The use of tools, be they material, digital or conceptual, is the crucial factor and their influence on the direction of work done is not merely important but frequently decisive. Put simply, new tools make possible the production of entirely new sorts of data, information, interpretation and, ultimately, archaeology (Lucas 2012, Reilly 1985, Reilly & Rahtz 1992a). In the 1980's archaeologists were embracing the rapidly expanding field of computer modelling and visualisation as vehicles for archaeological data exploration. Hypertext was also a very exciting emerging technology, and a number of innovative simulation studies evaluating survey methods and data had been published (e.g., Fletcher & Spicer 1988, Scollar 1969). Unfortunately, the inertia of pre-existing traditions of field recording practice and their epistemological assumptions had already largely been re-assimilated with little critical attention and now, propped-up by computerised scaffolding, were affixed with a veneer of self-evidence.

At that point in time an excavation was described as an 'unrepeatable experiment' (Barker 1993, 1). The challenge it seemed then was to overcome this perceived methodological oversight by demonstrating that the decisions on how to explore the raw archaeology would have a decisive influence on the reported outcomes. This could only be done with something that could be taken to pieces and explored repeatedly in many different ways.

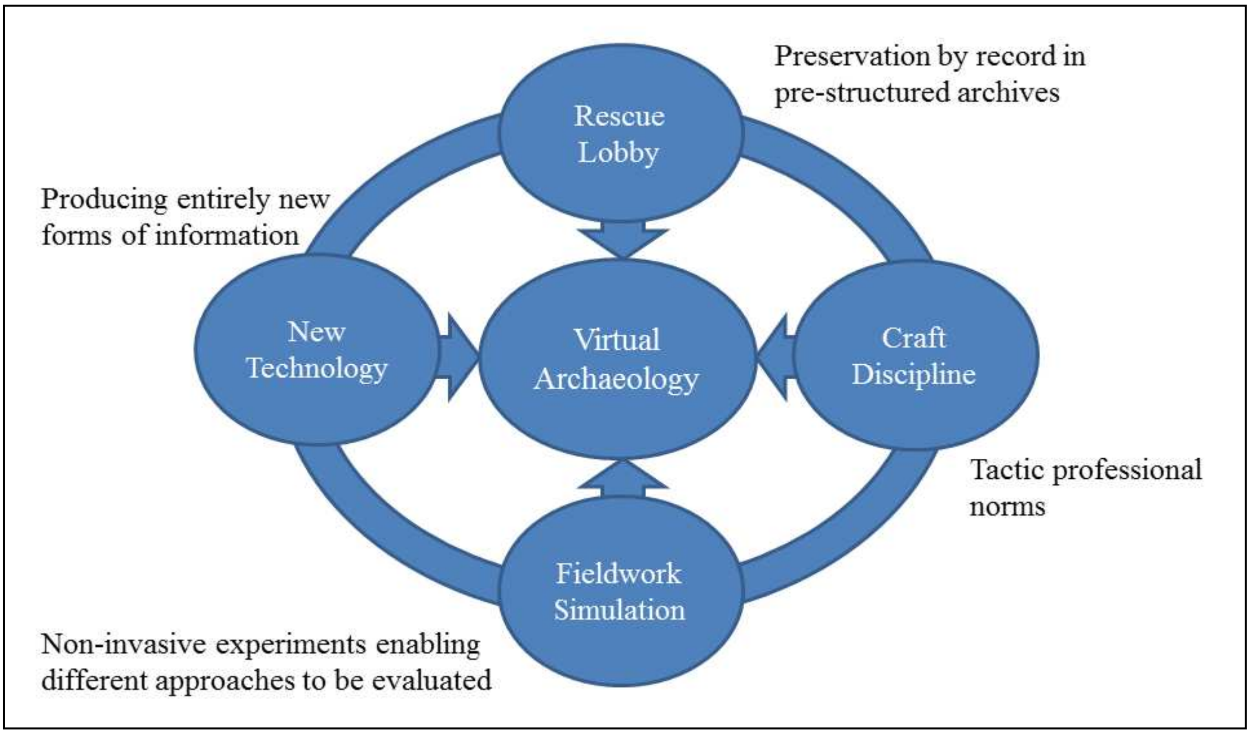

Figure 1 The origins of Virtual Archaeology.

The impasse was broken by invoking the concept of virtuality (Reilly 1991). Virtual archaeology described the way in which technology could be harnessed in order to achieve new ways of documenting, interpreting and annotating primary archaeological materials and processes, and invited practitioners to explore the interplay between digital and conventional archaeological practice.

An animated 3D computer model of a hypothetical excavation presented at CAA in 1990 (Reilly 2013) was the first example of applying solid modelling technology as virtual archaeology (Reilly 1991, 133–136). The intent was to incite, using the terminology of Bourdieu (1977), an 'epistemological rupture' in conventional archaeological recording and representation of excavation data by demonstrating the arbitrariness of conventions, such as sectional or plan drawings and photographs, whilst demonstrating the possibility of developing new, radical, recording strategies, the relative advantages of which could be examined, discussed and evaluated in a non-destructive disciplinary context.

In other words virtual archaeology was not only about 'what was' and 'what is', it was meant also to be a generative concept allowing for creativity and improvisation including 'what might come to be'.

2. The Relevance of Virtual Archaeology Today

During the period since its first articulation virtual archaeology has become predominantly associated with the use of 3D computer graphics within archaeological research. This is an association which has been established and reinforced through a long series of publications (Gutierrez *et al*. 2007, Pletinckx 2009, Wittur 2013). There can be little doubt that these activities form a part of what might be considered virtual archaeology but they do not comfortably define the limits of the original term.

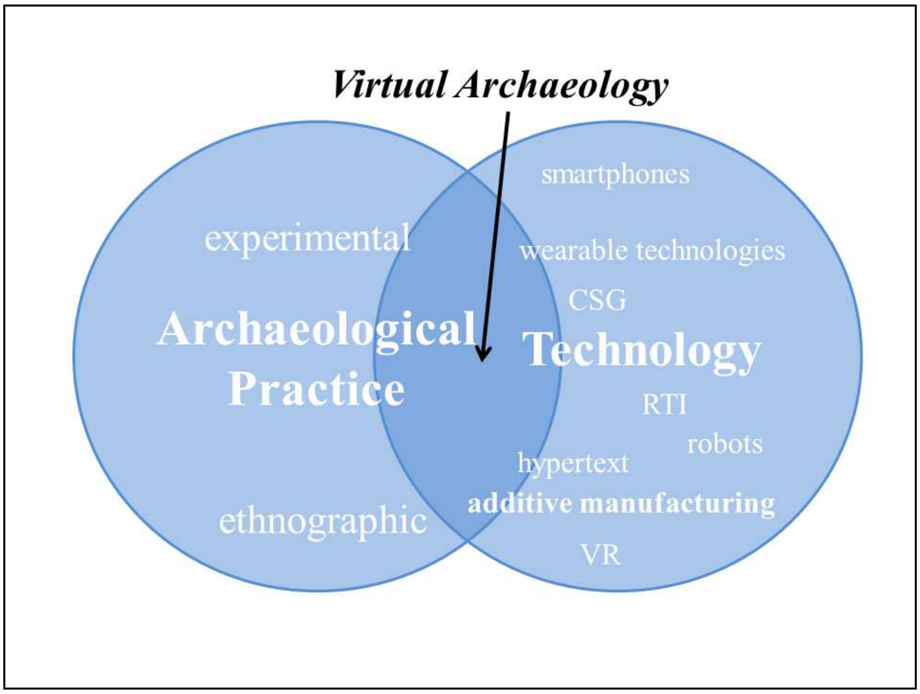

Figure 2 The spirit of virtual archaeology renders explicit the dynamic relationship between archaeological practice and technology.

Virtual archaeology, as first articulated, described the use of digital technologies as tools for mediating and engaging with conventional (analogue) archaeological processes. This definition was broad and potentially encompassed a wide range of technologies and processes. It should be made clear that the term 'virtual reality' was deliberately avoided and the importance of the non-graphical aspects of 3D computer modelling was highlighted (Reilly 1991, 1992). That an emphasis was placed on computer graphics is not surprising; the 1990s and 2000s saw rapid developments in this area accompanied by the falling costs of technology. However, reifying virtual archaeology into any specific technology amalgam is to miss the point.

The notion behind virtual archaeology was, and remains, useful for emphasising the intersection between technology and archaeological practice. For want of a better term, the *spirit of virtual archaeology* describes something which is inherently changeable, and which depends on the availability of technology and its potential utility within a specific situation be it in field or laboratory conditions (Fig. 2). Thus it was entirely natural that early papers which used the term *virtual archaeology* frequently dealt with the applications of 3D computer graphics, databases and hypertext. The specific technological emphasis says more about the state of technological development than it does about the essential meaning or relevance of the term. What remains of paramount importance is the need to focus on the practice of adopting technology as well as the technology itself. The ubiquity of digital devices within contemporary archaeological practice coupled with the proliferation of software with potential archaeological applications means that this need is greater than ever.

Recent technological developments have led to a proliferation of devices and software which augment, and often enhance, the human experience of the world. Consider, for example, wearable technology, the ubiquity of increasingly powerful smartphones, or the development of 3D printing. These technologies do not immerse but rather they augment. They allow the user to engage with the material world in tandem with digital technology. They are authentically tactile and blended with the physical world, offering renewed sensorial prominence and perhaps more cognitive depth through material engagement. Such technologies require a model of virtual archaeology which could not have been foreseen twenty years ago. However, the essential need to experiment with the use of technology, to play with it and to find new archaeological applications remains constant.

3. Virtual Archaeology Remains Useful

Many discussions regarding the epistemological status of virtual archaeology over the last two decades can be seen as an expression of a deeper anxiety discourse affecting *archaeological computing* in general (Ryan 2001, Frischer *et al.* 2002, Forte & Pescarin 2006, Pujol 2008, Llobera 2011, Huggett 2013, Forte 2014). Unfortunately, virtual archaeology became a contentious term in a way that other terms such as *archaeological computing* did not. This issue can be largely attributed to the fact that virtual archaeology became associated with a specific technology and a particular conception of how that technology might be used within archaeological practice. In fact virtual archaeology has suffered a similar fate to many other things which incorporated the word ‘virtual’, virtual reality being the prime example. This phenomenon is well documented elsewhere in the humanities, where J Stern (2003) has shown how the language of technology, and the misuse of this language, has been used to sell specific assumptions (academic and ideological) relating to technology. The challenge set by Sterne is to find a means of meaningfully appropriating new technology; to develop new conceptions of technology which are shaped by the intellectual themes and methodologies of our discipline (Sterne 2003, 370).

In the remainder of this paper we will draw on one contemporary technology: *additive manufacturing.* This potentially disruptive technology prompts us to re-engage with some of the core concepts of virtual archaeology, emphasising the fluidity of the term and the continued relevance of the conceptual framework which underpinned its initial use. The case study of additive manufacturing helps to demonstrate that beyond its association with specific technologies the *spirit of virtual archaeology* provides a mechanism for negotiating the use of any technology in archaeological practice.

4. The Spirit of Virtual Archaeology Re-Engaged

One popular example of additive manufacturing, known variously as consumer 3D printing, and rapid prototyping, is experiencing a great deal of hype at the moment. However, additive manufacturing, which, has been around longer than virtual archaeology, encompasses a set of far more mature technologies that have long since passed over the peak of inflated expectations, through the trough of disillusionment, and are steadily advancing up the slope of enlightenment to the stable plateau of productivity, according industry analysts (Gartner 2013).

At a very high level, the huge array of available additive manufacturing technologies can be loosely classified into three groupings. (For a full treatment see Lipson & Kurmar 2013). Selective extrusive printers in essence squirt, squeeze or spray pastes or powders through nozzles, syringes and funnels of all sizes to build up objects by depositing materials in layers. Selective binding printers by contrast, fuse, bind or glue materials together, again in a layers. The aforementioned technologies can, in one sense, be seen as producing analogue printing or additive manufacturing outputs using digital controllers. Currently at the cutting edge is true digital assembly using pre-manufactured physical objects. We can think of them as Lego blocks. However, precise assembly of billions of small physical voxels made in different and multiple materials remains a huge computational and fabrication challenge. Of course, hybrids, deploying multiple *print heads*, deploying various different fabrication methods, could also be configured.

Lipson and Kurmar (2013, 265) summarise the evolution of additive manufacturing as three episodes of gaining control over physical matter*;* control over geometry, composition, and behaviour.

First is an unprecedented control over the geometry, or shape*,* of objects. 3D printers can already fabricate objects of almost any material in any shape. Next is control over the composition of matter. We have already entered into this new episode where we go beyond just shaping external geometries to shaping the internal structure of materials with unprecedented fidelity, with the possibility of printing multiple materials including 'entangled components' which can be co-fabricated simultaneously. The final stage is control over the behaviour of materials, where they envisage programmable digital materials – made of discrete, discontinuous units – which are designed to function in a desired way, such as spongy, transparent, rhinoceros-shaped, in shades of grey and blue – perhaps even embedded with nano devices. Voxel-based printing affords the notion of different types of voxels (Hiller & Lipson 2009). Imagine, if you will, a library of archaeologically-defined material voxel types.

Control over *shape* provides a bridge between existing 3D modelling formats and the ability to repurpose them as 3D printed physical objects. Existing point clouds, terrain and solid models, indeed any system that can output STL format files can be 3D printed. By way of example, a 3D-printed map of the cone, crater, and summit of Mount St. Helens, Washington, USA, is available on Shapeways.com in three sizes (e.g., TinyMtn 2014), various other terrain models have been extracted from GIS systems for 3D printouts in South Africa (Agrawal *et al.* 2006), and geologists have 3D printed a stack of geology (i.e., stratigraphy) from north eastern Germany (Loewe *et al*. 2013). Although all these examples produce solid objects made in a single material, with the same density throughout, they nevertheless communicate in a very tangible fashion.

Makers print all kinds of materials: from bread dough, chocolate, and other food-based materials with their pronounced olfactory characteristics (which, incidentally, introduces another cross-sensory modality into the mix), to gypsum, sand, soil, terracotta, metal alloys, plastics and polymers. At a somewhat higher level of technological sophistication, and, commensurately funding, modern industrial additive manufacturing technologies span a wide spectrum of applications across a very broader range of scales: from bioprinting living ink; replacement body parts and prosthetics; manufacturing textiles; ceramics; glassware; jewellery; furniture; weapons; vehicle components: and innumerable parts and fixtures, including 3D printer components (Lipson & Melba 2013). Crucially, they can also combine *multiple entangled materials* (e.g., Vaezi *et al*. 2013, Vidimče *et al*. 2013).

Let us, as it were, step back and open the aperture of the nozzle, to demonstrate some more examples at a much larger scale and, perhaps, further afield. The potential of additive manufacturing, primarily in the form of 3D printing and rapid prototyping for archaeology and related disciplines is well established. For example, Midwest Studios 3D printed a highly detailed architectural model, for a new Carmelite foundation, designed as a classic French gothic monastery, including flying buttresses, for a growing community in Wyoming, USA, using the architect's (McCrery 2014) CAD files. In Europe, Swiss architects (Hansmeyer & Dillenburger 2014) created and 3D printed an ultra-modern, gothic-like, human-scale, immersive space dubbed the 'Digital Grotesque'. This room-like structure was assembled from 64 massive separate printed sandstone-like parts, containing 260 million surfaces printed at a resolution of a tenth of a millimetre. The 11-ton room took a month to print but only a day to assemble. Elsewhere, the European Space Agency and architects Foster+Partners are exploring the feasibility of building future moon-bases using fabricators exploiting local materials (i.e., regolith or lunar soil). Of course, at the moment, these projects require the use of terrestrial simulants, in other words materials with the same necessary material properties (ESA 2014).

Shifting the meaning of scale somewhat, 3D printing is already causing fundamental changes to our interactions with the finds record and other archaeological assemblages. The Smithsonian museum, for example, has embarked on the ambitious X3D project, which aims to digitalise all 137 million iconic items in its collection, and make them available for 3D printing anywhere in the world. In so doing, we should note, they are also making them available for transcultural discourses within *ethnographic archaeologies*, in the sense of Castañeda and Mathews (2008). Nowadays, virtual museums allow anyone to download and 3D print 'your own museum' (e.g., Lincoln 3D Scans 2014). Scholars have been sharing 3D printed artefacts for great academic profit for some while already.

Cuneiform tablets are the world's oldest known writing system. Older still are bullae, a form of Mesopotamian record-keeping technology in which accounting tokens were sealed inside hollow clay envelopes. Intact sealed bullae are extremely rare. Export of these priceless artefacts from their modern countries of origin (or discovery) and between the few existing major collections is, unsurprisingly, restricted. Nevertheless, specialists all over the world want to examine every minute detail of the tiny, fine characters, but photographs and drawings are generally regarded as inadequate transcription. Accessing the insides of the bullae is only conceivable using non-invasive methods (Marko 2014). An approach currently being developed combines CT scanning and 3D printing capabilities to enable detailed visual and tactile examinations with minimal handling so that originals can be safeguarded (Kaelin 2013).

These new objects may be (re)printed in different materials at different scales and the bullae facsimiles can be broken open to reveal sealed tokens within their interiors, and thereby made available for study without damaging the original artefacts. Such virtual artefacts, are easy to export electronically and download anywhere, rematerialised in any multivalent, transcultural space. Another form of additive manufacturing was employed by researchers in Wales to reverse engineer the construction of a medieval ship. The use of this technology not only produced an accurate geometric model to assist the reconstruction of a 15^{th} century ship found in the River Usk, it also demonstrated how material-characteristics can potentially be controlled to contribute to a better understanding of the original artefact's construction than is possible within traditional approaches (Soe *et al.* 2012).

5. Towards an Additive Archaeology

Let us now become more speculative, more aspirational, and explore some facets of additive manufacturing pertaining to materialisations of virtual archaeologies that might come to be.

As additive manufacturing evolved from producing primarily single-material, homogenous shapes to producing multi-material geometries in full colour with functionally graded materials and microstructures, it created the need for a standard interchange file format that could support these powerful new features. The response was the Additive Manufacturing File format (AMF), an open standard for describing objects for additive manufacturing processes such as 3D printing (AMF ASTM 2014). What is striking about the AMF format is that it encapsulates the typical recording sheet used on a modern archaeological excavation (Fig. 3), but does so in much finer *spatio-compositional*, that is in both macro-morphological and micro-morphological, detail.

If we did recast our recording method to generate contexts described in an AMF-like format, we suggest that archaeology would be a step closer to aligning the virtual and physical worlds, and a step closer towards the possibility of rematerialising archaeological *entities* found in the field.

What is to stop us from recording our excavations in such a way so as they can be refabricated? Current methods are clearly deficient. Here, by the way, we are not suggesting that all excavation should be 3D printed. We submit that if we recorded in such a way that we could rematerialise, or refabricate, our excavations in 3D then we would have improved substantively our practice.

Some will argue that current procedures are adequate for current needs. We counter, that in a uniquely destructive discipline, are we not ethically obliged to strive for superior recording practices?

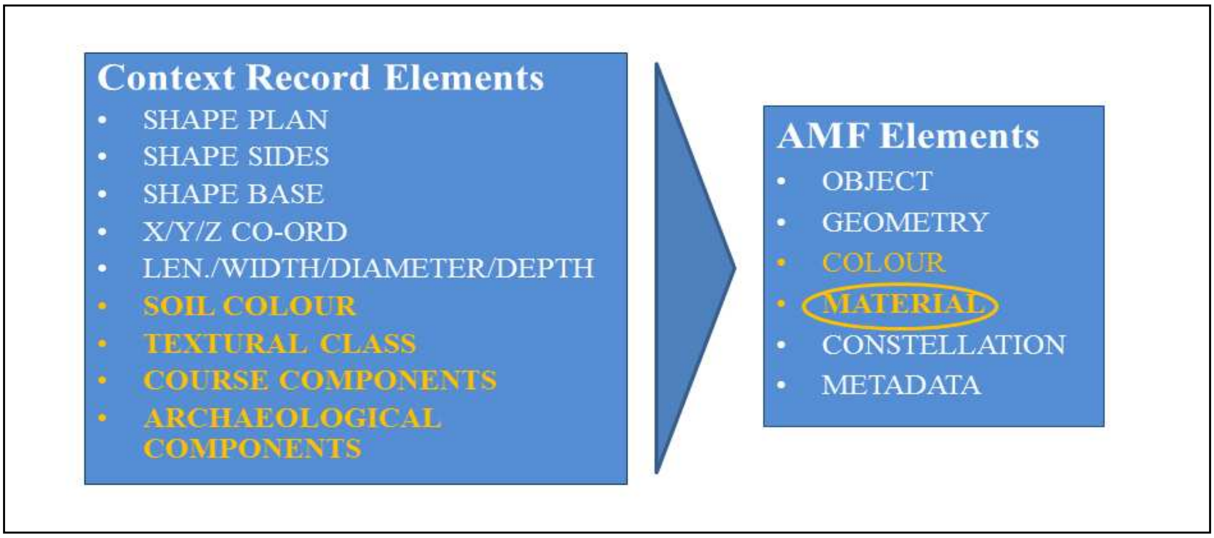

Figure 3 Materialisation: the AMF file format encapsulates all the elements of an archaeological context record making possible a closer alignment between virtual and physical worlds.

Glimpses of *additive archaeology*, which is just one particular echo of the spirit of virtual archaeology materialised through additive manufacturing, can be discerned already in the work of soil scientists and archaeologists conducting virtual excavations involving both scientific visualisations and 3D printing. For example, using a combination of Computed Tomography (CT) and 3D printing, soil scientists now have the ability to explore something so intricate and detailed as the structure of soil, close up, and set up multiple experimental investigations (Otten & Falconer 2014). Similarly, archaeologists can now disaggregate and re-aggregate non-intrusively a coin hoard found in one of two pots near Selby in the north of England. The CT data, which can be resolved down to two microns, were processed to produce an animation (Miles & Cox 2013) and extract 3D prints of some of the coins (Miles, 2012, Miles *et al.* 2014).

Conclusion

Additive manufacturing is just one technology enabling the *spirit of virtual archaeology* to generate new challenges to transform archaeological practice positively. Printing artefacts, monuments and cultural landscapes is established technologically and is already starting to disrupt both transcultural and disciplinary discourses and narratives as direct access these *e-cultural entities* by almost anyone, almost anywhere, to materialise them in any transcultural space, effectively disintermediates the opinions, interpretations and 'authority' of archaeologists and cultural resource managers. The implications of the above abbreviated, and much truncated, thesis for archaeology are immense. Releasing the spirit of virtual archaeology will add a technological nuance to the debate on the ontology of archaeology (Hamilakis 2014, 128).

We specifically contend that additive manufacturing provides a credible challenge to traditional archaeological practices (e.g., in recording). With this in mind, we want to respond to J Huggett's (2013) call for disciplinary 'grand challenges' for the next generation of archaeologists, so as to provide a catalyst for renewed innovation, strength of purpose, and direction in archaeological computing. We propose a disciplinary grand challenge to fabricate an excavation. That is an excavation rematerialised so as to be geometrically and compositionally accurate, whereby the curious can explore iteratively, reflexively, and comprehensively, the disaggregation and reassembly of archaeological entities encountered through archaeological intervention in such a manner as to engender a constant, multivalent, hermeneutic cycle between analysis and synthesis. We envisage that in striving to meet this challenge, the discipline will establish elements of an exemplary platform for strategic innovation, affording the development, and structured introduction, of innovative and distinctly archaeological approaches.

References

Agrawal, S., Antunes, J.P., Theron, E., Truscott, M. & de Beer, D.J. 2009. Physical modeling of catchment area by rapid prototyping using GIS data. *Rapid Prototyping Journal* 12(2): 78–85.

AMF ASTM 2014. F2915-13 Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1, ASTM International.
http://www.astm.org/Standards/ISOASTM52915.htm Accessed 28 August 2014.

Barker, P. 1993. *Techniques of Archaeological Excavation.* London: Routledge.

Bourdieu, P. 1977. *Outline of a Theory of Practice*. Cambridge: Cambridge University Press.

Castañeda, Q.E. & Mathews, C.N. 2008. *Ethnographic Archaeologies: Reflections on Stakeholders and Archaeological Practices*. Lanham: Altamira Press.

Derrida, J., 1996. *Archive Fever. A Freudian Impression*. Chicago: Chicago University Press.

ESA 2014. *Building a Lunar Base with 3D Printing.* http://www.esa.int/Our_Activities/Technology/Building_a_lunar_base_with_3D_printing, Accessed 28 August 2014.

Fletcher, M. & Spicer, R.D. 1988. 'Clonehenge: an experiment with gridded and non-gridded data', In *Computer and Quantitative Methods in Archaeology* 1988. Edited by S.P.Q. Rahtz, pp. 309–326. Oxford: British Archaeological Reports.

Forte, M., 2014 (forthcoming), 'Cyberarchaeology: a Post-Virtual Perspective', In *Humanities and the Digital. A Visioning Statement.* Edited by D.T. Goldberg and P. Svensson. Cambridge: MIT Press.

Frischer, B., Niccolucci, F., Ryan N. & Barcelò J.A. 2002. 'From CVR to CVRO: The Past, Present, and Future of Cultural Virtual Reality', In *Virtual Archaeology, Proceedings of the VAST Euroconference, Arezzo, 24–25*. Edited by F. Niccolucci, pp. 7–18. BAR International Series 1075. Oxford: Archaeopress.

Gartner. 2013. *Gartner's 2013 Hype Cycle for Emerging Technologies Maps Out Evolving Relationship Between Humans and Machines.* http://www.gartner.com/newsroom/id/2575515, Accessed 28 August 2014.

Gutierrez, D., Sundstedt, V., Gomez, F. & Chalmers, A. 2007. Dust and Light: Predictive Virtual Archaeology. *Journal of Cultural Heritage* 8(2): 209–214.

Hamilakis, Y. 2014. *Archaeology and the Senses: Human Experience, Memory, and Affect*. Cambridge: Cambridge University Press.

Hansmeyer, M. & Dillenburger, B. 2014. *Digital Grotesque*. http://www.digital-grotesque.com/, Accessed 28 August 2014.

Hiller, J. & Lipson, H. 2009. Design and analysis of digital materials for physical 3D voxel printing. *Rapid Prototyping Journal* 15(2): 137–149.

Kaelin, B. 2013. *Cornell Professors 3D Print Cuneiform Tablets* http://www.3dprinterworld.com/article/cornell-professors-3d-print-cuneiform-tablets, Accessed 28 August 2014.

Lincoln 3D Scans. 2014. *Lincoln 3D Scans lets you 3D print your own museum.* http://www.3ders.org/articles/20140202-lincoln-3d-scans-lets-you-3d-print-your-own-museum.html, Accessed 28 August 2014.

Lipson, H. & Kurmar M. 2013. *Fabricated: The New World of 3D Printing*. Indianapolis: Wiley.

Llobera, M. 2011. Archaeological Visualisation. Towards an Archaeological Information Science (AISc). *Journal of Archaeological Method and Theory* 18: 193–223.

Loewe, P., Klump, J. and Wickert, J. 2013. *Scientific 3D Printing: A Work in Progress Report.* http://www.slideshare.net/loewe/scientific-3d-printing-gfz-geoinformatics-kollquium-april-2012, Accessed 28 August 2014.

Lucas, G. 2012. *Understanding the Archaeological Record*. Cambridge: Cambridge University Press.

Marko, A. 2014. *The Modern Ancient Tablet. A curatorial intervention*. http://curatorialpracticum.wordpress.com/2014/05/04/the-modern-ancient-tablet/, Accessed 27 August 2014.

McCrery Architects. 2014. *The New Mount Carmel of America Monastery, Park County, Wyoming.* http://www.mccreryarchitects.com/portfolio/liturgical/new-mount-carmel-of-america/, Accessed 28 August 2014.

McGill, G. 1995. *Building on the Past: A Guide to the Archaeology and Development Process*. London: E & FN Spon.

Miles, J. 2012. *Computed Tomography scanning of Roman Coins.* http://acrg.soton.ac.uk/blog/1168/, Accessed 28 August 2014.

Miles. J. & Cox, G. 2013. *Animation showing Computed Tomography of coin hoard and visualisation of the hoard.* http://vimeo.com/45452797, Accessed 28 August 2014.

Miles. J., Mavrogordato, M., Sinclair, I., Hinton, D. and Earl, G. 2014. 'The Use of Computed Tomography for the Study of Archaeological Coins', In *Archaeology in the Digital Era. Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA'12). E-Proceedings. Southampton, UK, 26-30 March 2012.* Edited by G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska, & D. Wheatley. Amsterdam: Amsterdam University Press. http://dare.uva.nl/aup/en/record/500958, Accessed 10 October 2014.

Otten, W. & Falconer, E. 2014. 3D printed soil reveals the world beneath our feet. http://www.abertay.ac.uk/about/news/newsarchive/2014/name,15497,en.html, Accessed 22 March 2014.

Pletinckx, D. 2009. Virtual archaeology as an integrated preservation method. *Arqueologica* 2: 51–55.

Pujol, L. 2008. 'Does virtual archaeology exist?', In *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin, Germany, April 2–6, 2007. Kolloquien zur Vor- und Frühgeschichte, Vol. 10*. Edited by A. Posluschny, K. Lambers & I. Herzog, pp. 101–107. Bonn: Dr. Rudolf Habelt GmbH.

Reilly, P. 1985. 'Computers in Field Archaeology: Agents of Change?', In *Current Issues in Archaeological Computing*. Edited by M.A. Cooper and J.D. Richards, pp. 63–78. BAR International Series 271. Oxford: B.A.R.

Reilly, P. 1991. 'Towards a virtual archaeology', In *CAA90. Computer Applications and Quantitative Methods in Archaeology 1990.* Edited by S. Rahtz & K. Lockyear, pp. 132–139. BAR International Series 565. Oxford: Tempus Reparatum.

Reilly, P. 1992. 'Three-dimensional modelling and primary archaeological data', In *Archaeology in the Information Age: a global perspective*. Edited by P. Reilly & S. Rahtz, pp 145–173. London: Routledge.

Reilly, P. 2013. *Towards a virtual archaeology CAA 1990 abridged.* http://vimeo.com/77871447, Accessed 28 August 2014.

Reilly, P. & Rahtz, S. 1992a. 'Introduction: Archaeology and the information age', In *Archaeology in the Information Age: a global perspective*. Edited by P. Reilly & S. Rahtz, pp 1–16. London: Routledge.

Ryan, N. 2001. Documenting and Validating Virtual Archaeology. *Archeologia e Calcolatori* 12: 245–273.

Scollar, I. 1969. A program for the simulation of magnetic anomalies of archaeological origin in a computer. *Prospezioni Archeologishe* 4: 59–83.

Soe, S.P., Eyers, D.R., Jones, T. & Nayling, N. 2012. Additive manufacturing for archaeological reconstruction of a ship. *Rapid Prototyping Journal* 18(6): 443–450.

TinyMtn. 2014. *8″ Mt. St. Helens Terrain Model, Washington, USA.* http://www.shapeways.com/model/862887/8-mt-st-helens-terrain-model-washington-usa.html?materialId=6, Accessed 22 March 2014

Vaezi, M., Chianrabutra, S., Mellor, B. & Yang, S. 2013. Multiple Material Additive Manufacturing – Part 1: a Review. *Virtual and Physical Prototyping* 8(1): 19–50.

Vidimče, K., Wang, S.P., Ragan-Kelle, J. & Matusik, W. 2013. 'OpenFab: a programmable pipeline for multi-material fabrication'. *ACM Transactions on Graphics (TOG) - SIGGRAPH 2013 Conference Proceedings*, vol 32 (4), July 2013, Article No. 136, http://openfab.mit.edu/pdf/openfab.pdf, Accessed 3 November 2014.

Wittur, J. 2013. *Computer-Generated 3D Visualisations in Archaeology: Between Added Value and Deception*. BAR International Series 2463. Oxford: Archaeopress.