Invited Paper

High Quality Digital Imaging of Art in Europe

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Abstract

In the past decade various museums and galleries around Europe have been developing digital imaging as a tool for archiving and analysis. Accurate digital images can replace the conventional film archives which are not stable or accurate but are the standard record of art. The digital archives open up new research possibilities as well as becoming resources for CD-ROM production, damage analysis, research and publishing. In the VASARI project new scanners were devised to produce colorimetric images directly from paintings using multispectral (six band) imaging. These can produce images in CIE Lab format with resolutions over 10kx10k and have been installed in London, Munich and Florence. They are based around a large stepper-motor controlled scanner moving a high resolution CCD camera to obtain patches of 3kx2k pels which are mosaiced together. The scanners can also be used for infra-red imaging with a different camera. The MARC project produced a portable scan-back, RGB camera capable of similar output and techniques for calibrated printing. The Narcisse project produced a fast high resolution scanner for X-radiographs and film and many projects have worked on networking the growing number of image databases.

This paper will present a survey of some key European projects, particularly those funded by the European Union, involved in high resolution and colorimetric imaging of Art. The design of the new scanners and examples of the applications of these images will be presented.

1. Introduction

Digital images are becoming increasingly important in museums and galleries. Not only are they a valuable resource for producing multimedia products but with developments in high quality imaging, they are gaining acceptance for complementing or replacing photographic archives. Early public-access systems such as in the Musée d'Orsay in Paris showed around 5000 24 bit images at 1kx1k resolution. These were of very high quality for there time and illustrated what was becoming possible with digital images. Many other public access systems have since been developed, often using 8 bit colour mapped images to save space: such as in the MicroGallery at The National Gallery in London. These systems often have low resolution images (around 500x500) which are sufficient for reference and fast to access.

Although low resolution scans of transparencies are useful for multimedia production they are insufficiently accurate for some research, or of high enough resolution for printing. Conventional film archives are not permanent so they must be replenished by costly re-photography. While professional photography is relatively accurate it is not consistent or quantitative. The best accuracy that can be expected from film[1] is around 8 ΔE (CIE L*a*b*) units average for a MacBeth ColorChecker[2] chart. Digital imaging of art has approached 1 ΔE unit using the VASARI scanners. The high resolutions available with large format transparencies are possible with digital imaging (up to 20kx20k), with the added benefits of calibrated colour and stability. Digital imaging has clear advantages compared to conventional photography but requires extra training, computing infrastructure and investment.

While direct imaging of objects is the most accurate method of image capture there are large photographic archives of transparencies, X-radiographs and other material which in some cases is unique. The Narcisse project[3] (April 1990-Dec. 1993) developed a scanner to rapidly produce high resolution images from large X-radiographs and transparencies. It scans at up to 6000x8000 over an area up to 35cm x 43 cm in only 9 seconds.

The VASARI project[4] (Visual Arts System for Archiving and Retrieval of Images) designed and produced scanners to capture images directly from paintings. The system moves a high resolution CCD camera over the painting area capturing patches which are later joined together. A multispectral (6 band) image is obtained using filtered illumination, calibrated to CIEXYZ and stored in the CIE colour space[5] L*a*b*. Three scanners now exist: in The National Gallery London, the Doerner Intitut Munich and the Uffizi Gallery Florence (made in the MUSA project).

The MARC project[6] (Methodology for Art Reproduction in Colour) concentrated on perfecting the path from accurate imaging to accurate printing. A more conventional RGB system is used in a new portable scan-back camera capable of 20kx20k resolution. However a similar calibration technique to that used in VASARI produces very accurate images in the same device-independent colour space (CIE Lab).

Figure 1 shows a schematic diagram of the principle difference between the VASARI and MARC camera systems. The 6 band VASARI scanner moves the camera and fibre-optic lights while the RGB MARC camera moves the CCD in the image plane and uses conventional fixed photographic lights.

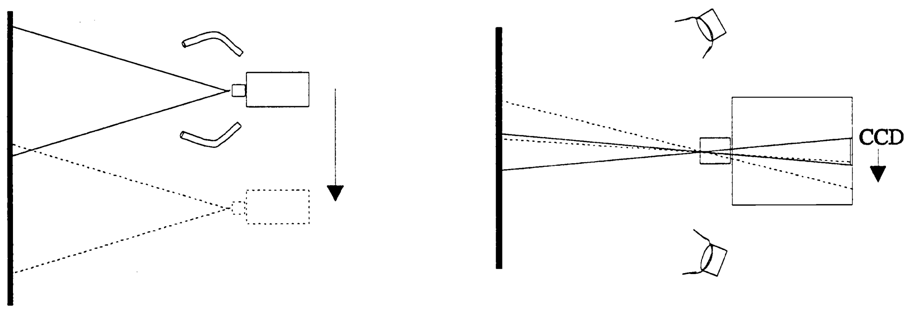

Figure 1 Schematic diagram of the VASARI scanner (left) and MARC camera

2. The VASARI scanners

The VASARI project produced scanners which move a monochrome CCD camera on a stepper-motor controlled platform to capture "tiles" which are mosaiced into complete images. The scanner in London is shown in Figure 2 and shows the vertical stepper-motor structure which can be manually moved back on rails to allow easy access with a painting. Mounted behind the camera (not seen in this photograph) is the 24V DC illumination system which feeds light through glass fibre-optics to the painting. The Kontron Progres camera was used to provide 3kx2k pels per tile. The resolution was set to around 20 pels per millimeter of painting in order to capture crack patterns and produce detailed images which are still of high enough resolution for printing. The captured images are calibrated to CIE Lab colorimetric values and stored as 32 bits per pel. Thus the final calibrated image file size is dependent on the painting size but is in the order of 1.5GB per square metre at 20 pels/mm. Instead of using conventional red, green and blue colour separations, six filters (with a 70nm width) spanning the visible spectrum are used. The raw uncalibrated data is much larger: 2.4 Gbytes/m^2 (for 8 bit capture). The camera has recently been replaced with the 12 bit ProgRes 3000 camera so this volume has potentially doubled. However due to the noise characteristics of the signal, companding it to 8 bits with a square root does not loose a significant amount of information.

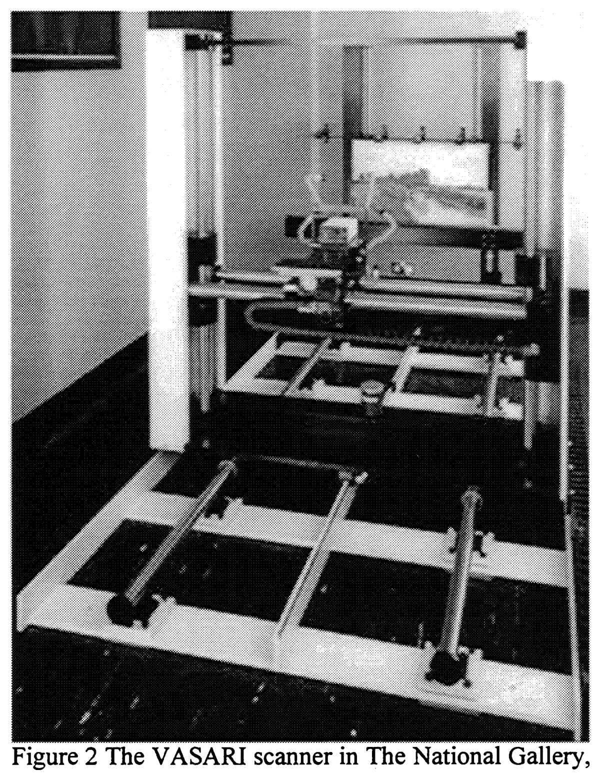

Figure 2 The VASARI scanner in The National Gallery, London.

Before each scan an image is taken of a smooth PTFE target and a MacBeth Colorchecker chart, which has been spectrophotometrically measured. Using these known measurements, a calibration matrix is generated which is used to convert the object image to CIE XYZ. This is converted to CIE Lab for storage (see section 3). The calibration is described more fully elsewhere[4]. It is assumed that the camera values (v) are related to the real XYZ values (c) in a simple linear system where F is an unknown set of coefficients:

$$c = F.v$$
$$F = \left[(C^T C)^{-1} C^T V \right]^T$$

By imaging a set of known colour values (C) from a colour chart and obtaining a set of camera values (V), the unknown calibration matrix F is found using a least-mean-squares solution shown in the second equation above. This allows an over-determined solution where all the 24 Macbeth chart patches contribute to the solution. Images of the paintings are then converted using the calibration matrix into CIE XYZ, then to CIE Lab based on a D65 illuminant. Lab space provides a more visually uniform quantisation of colour space. One unit distance in Lab space is very close to one just noticeable difference. One problem with the least-mean squares fit to XYZ is that the errors are not visually uniform. This was addressed in the MARC project.

Before scanning can begin with a VASARI scanner, the resolution in pels per millimeter is measured by moving the camera known distances sideways and finding how far an edge on a target has moved. An automatic focus is also used by moving the camera axis, grabbing frames and calculating an entropy value which is related to the focus. This is used to reposition the camera to obtain the best focus rather than adjusting the lens, so the resolution is fairly repeatable from between scans. During the capture phase the scanner moves the camera using a stepper-motor system to provide an array of 3kx2k patches overlapping by around 200 pels. The overlaps are analysed for tie points using correlation and these are used to provide an exact join of the patches. This technique replaces the need to have a more expensive scanner with extremely high precision and also compensates for other mechanical and optical distortions.

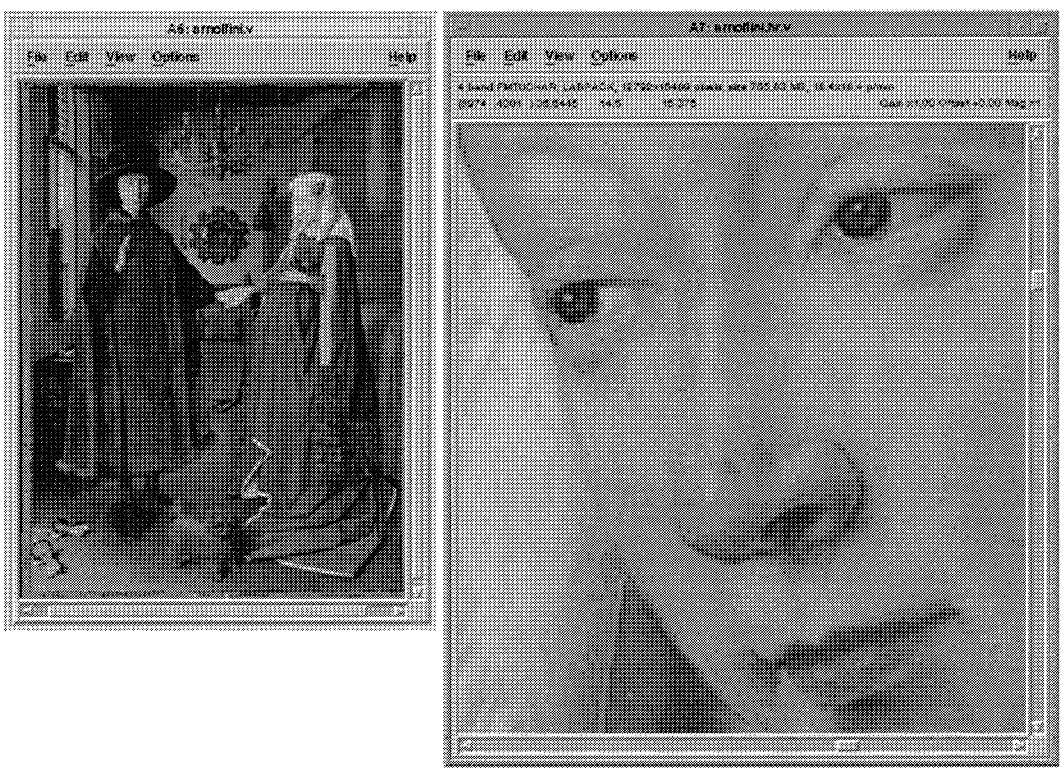

Figure 3. View of a 12kx15k image from the National Gallery VASARI scanner, "The Marriage of Giovanni (?) Arnolfini and Giovanna Cenami (?)" by Van Eyck (1492).

Non-uniformities due to variations in dark-current and sensitivity of the CCD sensor are removed in the calibration stage. A dark current image is taken with the lens cap on and used to subtract the varying offsets. Because the lights move with the camera, they provide a consistent illumination pattern which can be measured by imaging a smooth white PTFE target. This also helps compensate for variations in sensor gain.

Initially three sets of VASARI images were kept: the original data, the XYZ calibrated data and an RGB display version. This has been simplified by keeping the raw data and the calibrated CIELab image, from which RGB for display is calculated on the fly in the viewer (ip[7]). Figure 3 shows the ip program viewing a 755 Mbyte image. As the scroll-bar or region selector box is moved the new image areas are paged in by the virtual memory system. The software runs on a Unix workstation and uses X11/Motif. The files are archived on DAT tape and Magneto-Optical disks.

3. The MARC camera

The MARC project produced a new scan-back camera[8] where an array CCD is moved in the image plane of a conventional large format camera by the use of a precise stepper motor system. This was designed and built in the Technical University in Munich. The CCD is the RGB striped, 2/3" interline transfer device used in the ProgRes cameras. It has 500x582 elements with small (6μm), widely separated (11x17μm) sensor sites. Rather than moving the sensor with piezo-electric actuators the fine stepper-motor stage is used. Also for consistency only one field is used to acquire 500x290 pels at 10 MHz. The microscanning action produces a 3k x 2k image of a small area in the image plane. Macro-scanning steps the CCD to a fixed array of 7 by 9 positions so the final image resolution is 20k x 20k. The fixed positions can be calibrated so that the small overlap is more repeatable.

For the MARC camera each 3kx2k patch has a slightly different gain characteristic due to the variations in angle of the incident light, especially noticeable at the edges of the image. To compensate for this a full-field calibration target is used and a 7x9 set of correction factors obtained. At the acquisition stage the overlap areas are stored so the calibration stage can compute the correction factors.

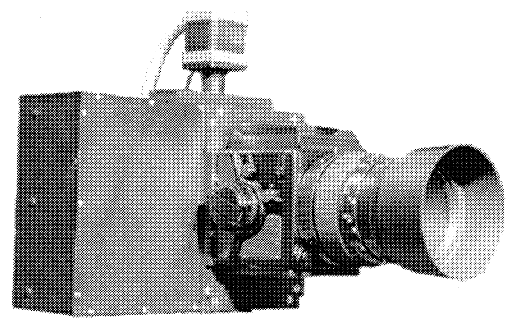
Figure 4. The MARC camera

The colour calibration is more developed than the linear model originally used in the VASARI project. It minimises the fit error in Lab space rather than XYZ, which leads to a more visually uniform error distribution as well as a lower average error. The final images have an average Lab ΔE of around 3.

The project also developed an SBUS interface for the camera which could also be used to connect the ProgRes cameras in the VASARI scanners. This allows DMA capture directly to memory at rates limited only by the A/D conversion and micro/macro scanning. Each field requires 40ms light integration and 40ms positioning, which leads to a minimum capture time of 15.36s per 3kx2k patch. In practice the extra time to save to disk adds a small amount of time to this, as well as the wait time to the next field start. The actual acquisition system has to assemble a green channel image in memory so it can save the overlap regions separately for later analysis.

A quantised Lab standard was required for the final calibrated images. Printing tests showed that the 8 bits per channel used commonly in TIFF for example can lead to contouring when printed. This led to the MARC project standard (LabQ) of 10 bits for L and 11 bits for each of a and b, producing an efficient 32 bit colour value for use in display and printing. The ten bits for L may seem low given the initial twelve bits per channel but L is a visual quantisation and includes a companding effect. A non-standard (VIPS[9]) image format is used which was developed in the VASARI project. It has a fixed size header and no line padding so that it can be mapped into virtual memory without the problems found in formats such as TIFF.

Table 1 below outlines some of the differences between the VASARI and MARC acquisition systems. The MARC camera can be moved around easily with a SUN workstation or SBUS-equipped laptop. The power consumption of the photographic lights is probably the factor which most restricts portability. Natural light could cause problems due to temporal changes, as would any movement in the object: these systems are really designed for use in a controlled environment. Images from the VASARI scanner have a different texture than those illuminated by large paired photographic lights due to the anular nature of the illumination used. The fast mechanics of the MARC camera and single-field grabbing allows a preview image of the scan area to be made very quickly compared to the VASARI scanners. Also a focus value (and corresponding sound of increasing frequency) derived from an entropy value can be used while the operator changes the focus of the lens. The VASARI scanners do this by moving the camera axis automatically. Currently there is no physical resolution measurement with the MARC camera so real scale is lost. This may be a future addition because it was found to be useful in the VASARI images.

In both systems the calibration time is relatively long and is usually carried out after the complete acquisition, or even over-night. In a recent scan with the MARC camera the 6k x 10k acquisition took 14 minutes and 45 minutes to calibrate on a 50 MHz SPARC system. Both processes are not yet fully optimised, so considerable speed-increases are possible, especially through using a faster disk system and multiple, faster CPUs.

VASARI scanner	**MARC camera**
not portable	fairly portable
object size limited by mechanics	size limited by illumination and position
pels/mm resolution known	not known automatically
localised lighting effects	lighting looks same as photograph
Illumination pattern corrected	difficult to correct
Objects must be fairly planar	3D objects possible
Preview and acquisition is slow	Preview and acquisition is much faster
colour accuracy higher	RGB system slightly less accurate

Table 1 Comparison of VASARI and MARC imaging

The MARC project began in September 1992 and ended in 1995 with a demonstration catalogue of Netherlandish art from the Bavarian State Galleries in Germany, produced by the new camera and a calibrated printing press. The National Gallery in London has carried out trials in their photographic studios and the Byzantine Museum in Greece has recently installed a MARC camera.

4. Infra-red and X-ray Imaging

Figure 5 X-radiograph of painting by Dujardin

X-radiographs and infra-red images of paintings are made routinely for documentation and research. X-ray images show canvas structure, supports and underpainting for example. The X-ray films can be scanned at high resolution and used together with visible images for greater analysis. There is currently no standard use of solid state X-ray sensors for direct imaging due to the high costs involved. X-radiographs show contruction details such as wooden supports and nails, as well as underpainting. The texture of the canvas is also very prominant. An example is shown in Figure 5 which shows two versions of the face and a vertical wooden support down the centre.

Paint layers tend to be transparent to infra-red so imaging in this region is extremely useful in recording the initial drawings in charcoal for example. These images can show how the composition was changed by showing the original sketches underneath the paint and are extremely useful to researchers. At the National Gallery in London a Hamamatsu tube-based camera is still used but produces good results with automatic level balancing to compensate for the drifts in the average signal. A motorised easil is used to obtain a patchwork of low resolution images which are assembled using the VASARI mosaic software to produce high resolution images. The scanner in the Doerner Intitute in Munich has an infra-red camera mounted as well as the ProgRes camera. By overlaying infra-red and visible images[10] the under-drawing can be more easily compared with the visible images. Figure 6 shows a detail of an infra-red image from The National Gallery, which shows a different drawing with the mouth to the left of the final one. Solid state cameras are available with the necessary response (around 1-2μm wavelength) but their use is currently restricted due to their high cost. These provide a more stable signal and good geometry. Although conventional CCD cameras have some infra-red response, unfortunately it does not reach far enough into that region so separate cameras will be requred for the foreseeable future.

Figure 6, Detail of infra-red reflectogram of *Christ before pilot* by the Master of Cappenburg.

5. Applications and the future

Although high quality digital imaging of art is now available, it is only just beginning to replace conventional photography. This is due to many factors such as investment costs and training, but also because of a lack of understanding of its potential. However there is now a growing interest in using digital imaging, particularly for publication and CD-ROM production. Higher quality image archives will soon become available in access points in the form of personalised colour prints for example. It is only with time that a complete understanding of the inevitable changes to art distribution will become possible. The spread in the use of high resolution display systems in museums is one illustration of a trend which depends on the increasing quality of digital art images, yet is more dependent on institution policy and funding than technology.

The development of high quality imaging of art not only increases the quality of image archives but has led to new research possibilities. With accurate colour measurements colour research is no longer limited to spot readings and studies of colour fading or changes due to cleaning are now possible. The high resolution of these images also allows changes in cracks and surface texture to be measured[11]. The various types of image, such as infra-red and X-ray images, are now becoming digital. This has allowed more direct comparisons than with the old film versions and will lead to a wider availability of these materials for researchers. The Research Laboratories of the Museums of France (LRMF) in Paris has produced a CD-ROM containing technical images of paintings by Poussin which illustrates this well. The growing trend to make images available via the World Wide Web will hopefully encourage a use of standards and calibration, although at the moment most images are uncallibrated. If bandwidth increases in the Internet outweigh the massive growth in use, higher resolution image browsing will become more accessible, although copyright issues with these images may necessitate charging mechanisms. It is still unclear whether art institutions can produce worthwhile incomes from Internet distribution in the way that CD-ROMs have allowed.

It is the growing acceptance of device-independent colour which is vital to the wider use of accurate colour images. Commonly used programs such as Adobe Photoshop recognise CIE Lab and various colour management systems exist but it is still difficult to obtain a calibrated image, or know when one is accurate or simply the result of a conversion from an unknown RGB image. It is hoped that the pioneering projects outlined here will help the development and uptake of this technology. This will greatly enhance the accuracy of art images, which are becoming more accessible through networks and CD-ROMs.

6. Acknowledgments

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7. References

1. N. Ohta, "Colorimetric Analysis in the Design of Color Films: A perspective", *Journal of imaging science and technology*, Vol. 36, No. 1, 1992.

2. C. S. McCamy, H. Marcus and J. G. Davidson, "A color-Rendition Chart", *Journal of Applied Photographic Engineering*, Vol. 2, No. 3, 1976.

3 C. Lahanier, G. Aitken, M. Aubert, "Narcisse: bonne résolution pour l'étude des peintures", *TECHNÈ*, Vol. 2, pp 178-190, 1995.

4. K. Martinez, J. Cupitt, D. Saunders, "High resolution colorimetric imaging of paintings", *Proc. SPIE*, Vol. 1901, pp 25-36, Jan 1993.

5 Commission Internationale de l'Éclairage, "Recommendations on uniform color spaces, color difference equations, psychometric color terms", Supplement No.2 to *CIE Publication No.15 (E-2.3.1), 1971/(TC-1.3)*, 1978.

6. H. Derrien, "MARC, a new methodology for art reproduction in colour", *Information Services & Use*, Vol. 13, No. 4, pp 357-369, 1993.

7. J. Cupitt, K. Martinez, "Image processing for Museums", in *Interacting with images*, eds L. MacDonald and J. Vince, pp 133-147, John Wiley, 1994.

8. R. Lenz, R. Beutelhauser and U. Lenz, "A microscan/macroscan 3x12 bit digital color CCD camera with programmable resolution up to 20,992 x 20,480 picture elements", in Proc. of the Commission V Symposium *Close range techniques and machine vision,* Melbourne, Australia, , Intl. Archives of Photogrammetry and Remote Sensing, Vol. 30, part 5, 1-4 March 1994.

9 J. Cupitt and K. Martinez, "VIPS: An Image Processing System for Large Images", Proc. IS&T/SPIE Symposium on Electronic Imaging: Science and Technology, Very High Resolution and Quality Imaging, Vol. 2663, Jan. 1995.

10. D. Saunders and J. Cupitt, "Elucidating Reflectograms by superimposing Infra-red and Colour images", National Gallery Technical Bulletin, Vol. 16, pp 61-65, 1995

11. A. Burmester, J. Cupitt, H. Derrien, N. Dessipris, A. Hamber, K. Martinez, M. Müller, D. Saunders, "The examination of paintings by digital image analysis*", Proc. 3rd International Conference on non-destructive testing, microanalytical methods and environment evaluation for study and conservation of works of art*, Viterbo, Italy, pp 201-214, Oct. 1992.