TRADITION AND INNOVATION
ADVANCES IN CONSERVATION

Contributions to the Melbourne Congress
10-14 October 2000
RECENT APPLICATIONS OF DIGITAL IMAGING IN PAINTING CONSERVATION: TRANSPORTATION, COLOUR CHANGE AND INFRARED REFLECTOGRAPHIC STUDIES

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ABSTRACT
In recent years digital imaging has proved to be a useful tool for documenting and examining paintings. These techniques can yield permanent records that are potentially more accurate than photographic images. The key applications in which digital imaging is superior to other techniques are those where short- or long-term changes are measured. The paper describes the imaging systems developed in a ten-year collaboration between the National Gallery, London and the Doerner-Institut, Munich and the geometric transformation algorithms which have allowed accurate comparisons of 'before' and 'after' images to be made. Recent results obtained from a long-term study of colour changes caused by display in the museum and short-term changes caused by transportation to loan exhibitions are presented. Improvements made to the procedure for acquiring, processing and presenting infrared reflectograph mosaics are also detailed. Finally, other conservation-related and archival uses for the colour-accurate, high-resolution digital images are discussed.

INTRODUCTION
In the four decades since the IIC Rome Conference the increased use of computers and their greater sophistication has opened new possibilities for the application of digital imaging in conservation. To date, there have been examples of successful applications of imaging techniques in documentation and examination of works of art. However, many of those applications lack convincing advances over existing, traditional methods. For example, there are instances of image-processing algorithms being used to enhance visibility in very poor quality X-radiograph images when a new exposure could have been made, expending less time and resources. During our research and subsequent work we have noticed that not only does digital imaging allow permanent records of a work of art to be made that are potentially more accurate than photographs but that, even more importantly, these can act as a 'baseline' against which to compare images of the same object made at a later date. This comparison has proved to be the key application for digital imaging, which cannot easily be accomplished by the human eye or other conventional methods.

To realize this potential the National Gallery, London and the Doerner-Institut, Munich have collaborated for more than a decade in the development of high-resolution digital imaging systems and their application to painting conservation issues [1]. Particularly long-term changes caused by display and short-term changes caused by transportation to loan exhibitions or conservation treatment.

Before such studies were possible, a method of obtaining accurate, reproducible images of paintings was needed. Until recently, no commercially-available camera was capable of producing images of sufficient quality to allow such comparisons between different 'states' of a painting to be made; one example is the condition of an object before and after transportation. It became clear that the first stage of the project would be the design and building of an imaging system.

DEVELOPMENT OF IMAGING SYSTEMS IN LONDON AND MUNICH
Two imaging systems have been developed as a result of our collaboration, each named after the European Community supported project out of which they arose. Here we provide brief descriptions, as more details have appeared in previous publications.

VASARI
The VASARI (Visual Arts: System for Archiving and Retrieval of Images) imaging systems were constructed in London and Munich between 1989 and 1992 to allow images of paintings to be made with a resolution of up to 20 pixels per millimetre on the painting surface [2]. In essence, the systems in each city are the same, but they differ in appearance as some of the bulkier components were purchased locally; the Munich scanner is built from modular components used in industrial robotic applications, which allow the system to be configured rapidly for different applications [3]. In both systems, paintings are placed on a rigid easel and images are made by moving a camera across a plane parallel to the painting surface using the accurate mechanical positioning (robotic) system. Depending on the application, the camera can be either a monochrome digital camera or an infrared Vidicon system. To obtain sufficient resolution, images are made of a small portion of the painting; these sub-images are calibrated, corrected and assembled into an image of the whole painting [3, 4], rather like the tiling on a bathroom wall.

In the London system, colour information is obtained by making a series of images of each sub-area while illuminating the surface with light transmitted by one of a series of broad-band interference filters; typically seven bands, from 400 (violet) to 700 nm (red) are used. Calibration targets allow accurate colour measurements to be derived from the seven-band data. The colour information is stored as standard CIE L*a*b* colour co-ordinates [5], although the seven-band data are also archived. Colour accuracy is determined by comparing the colour data obtained from measuring a set of 24 colour standards with their absolute colour data, measured spectrophotometrically. Initially, the average error in the colour measurements over these 24 samples was around 2.3 ΔE*a*b* units (roughly one ΔE*a*b* unit corresponds to a just-visible difference), but refinements in the calibration process over 10 years have reduced this to 1.1 ΔE*a*b* unit. The main drawbacks of the VASARI systems are that they are more or less immovable once installed and can only measure smaller paintings (up to 1350 × 960 mm), although the system in Munich has been used to image larger paintings, such as the two panels of Dürrer's 'Vier Apostel' (Bayerische Staatsgemäldesammlungen, Munich Nos. 545 and 540) each measuring about 212 × 76 cm, by twice changing the position of the painting on the easel. The final infrared image of each painting comprised around 600 single frames [6, 7].

MARC
The MARC (Methodology for Art Reproduction in Colour) camera effectively combines the VASARI scanner and its camera into a single compact unit. It was developed during the eponymous project from 1993 to 1996, is portable and, with appropriate optics, can image paintings of any size [8]. In the MARC camera, a colour image is made in a single long exposure, during which the charge-coupled device (CCD) sensor is translated in two dimensions across the focal plane. The photosensitive sites on the CCD are masked with red, green or blue filters, allowing colour information to be derived from the raw camera data. A colour target and a calibration process similar to that used in the VASARI system allow accurate colour data to be obtained. Initially, the colour error of the MARC camera was of the order
of 3 $\Delta E^{*}{ab}$ units, but this has recently been reduced to c. 2 $\Delta E^{*}{ab}$ units, principally by the introduction of new HMI (halide metal inert gas) light sources for imaging.

**IMAGE CORRECTION AND COMPARISON**

Equipped with imaging systems that can provide high-resolution images with accurate colour, it has been possible to examine short- and long-term changes in paintings associated with periods on display, transportation to exhibitions and conservation treatment. An essential part of such comparisons is a method of bringing the ‘before’ and ‘after’ images into exact superposition; memory alone, or comparison of ‘before’ and ‘after’ photographs, are not adequate for such a task.

There are two principal causes of geometric differences between ‘before’ and ‘after’ images. First, changes in the imaging equipment and the imaging set-up, which cause differences in scale, rotation and perspective created by slight differences in angle between the painting surface and camera focal axis during discrete imaging sessions. The second cause of geometric differences is change in the object, for example warping caused by variation in relative humidity. We have described previously a simple method by which images may be brought into superposition using translation and scaling alone [9]. In the studies reported here we have used a more sophisticated second-order ‘rubber sheathing’ technique to transform one image to ensure correlation with a second.

Figure 1 shows a classification of types of geometric distortion: types 0, 1 and 2 are typically caused by acquisition errors, while type 3 or higher changes are usually associated with a change in the object. Higher order corrections have not been used, as we must compromise between the need to correct for differences in image acquisition parameters, and the possibility of removing relevant alterations in the geometry of the object.

Once a type of geometric change has been chosen which will bring two images into alignment, the problem is to determine parameters for the model. For a type 2 transformation, for example, eight constants must be calculated, c1 to c4 for both x and y directions (Fig. 1). Values must be selected that minimize average differences between the two images over the whole of their surfaces, which can be a very time-consuming problem, typically requiring the selection of many tie-points. Fortunately, if the images being compared are sufficiently similar, it is possible to use entirely automatic procedures to derive the parameters to a high degree of accuracy [10]. This automatic procedure has made it possible for us to compare very large images taken many years apart.

The procedure has some limitations. The transformation cannot be applied to pairs of images that have very different content, for example an image of a painting and its X-radiograph, and, as mentioned above, may compensate for certain changes, such as deformation of a stretcher during transportation, that are not due simply to differences in the image acquisition geometry.

<table>
<thead>
<tr>
<th>Painting</th>
<th>First imaged</th>
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<tbody>
<tr>
<td>Workshop of Campin, The Virgin and Child in an Interior, NG No. 6514</td>
<td>May 1993</td>
</tr>
<tr>
<td>Master of Liébana, The Adoration of the Kings, NG No. 258</td>
<td>March 1994</td>
</tr>
<tr>
<td>Van der Weyden, The Magdalen Reading, NG No. 654</td>
<td>February 1995</td>
</tr>
</tbody>
</table>

(a) NG No. is the National Gallery, London, acquisition number.

**CONSERVATION APPLICATIONS**

**Colour difference**

The digital imaging techniques developed in the VASARI project are designed to allow the detection of differences in colour between two images, so that any long-term colour changes can be detected in paintings imaged at different times. The project is the successor to previous spectrophotometric [11] and image-processing methods of detecting colour changes [12, 13]. In an interim study, colour information from the VASARI scanner was compared with that from spectrophotometric measurements made in the 1980s; no changes were detected in the colour of the paintings examined [14]. Now that some years have passed since the first VASARI colour images were made [15], meaningful comparisons between images can be made.

The type 2 transformation has been used to bring images made in 1999 into superposition with those made earlier in the decade (Table 1). Once the images coincide, the colour difference ($\Delta E^{*}{ab}$) between individual pixels can be determined using a simple colour difference equation (a process described in more detail elsewhere [4]):

$$\Delta E^{*}{ab} = (\Delta L^* a^{*2} + \Delta L^* b^{*2})^{0.5}$$

where $\Delta L^*$, $\Delta a^*$ and $\Delta b^*$ are the differences in the values of $L^*$, $a^*$ and $b^*$ stored for the ‘before’ (c. 1994) and ‘after’ (1999) images. The $\Delta E^{*}{ab}$ values can be presented as a scaled monochrome image, in which white areas represent the largest changes in colour and black areas indicate that no change has occurred.

One example has been chosen to illustrate our findings. The image in Figure 2a is such a monochrome representation, showing colour differences between the images of The Virgin and Child in an Interior by the workshop of Campin, made in 1993 and 1999; for reference, the image made in 1999 is shown in Figure 2b. The average colour change across the whole image has not been calculated, as there are some differences between the images, explained below, that would render this figure meaningless. Instead, the average colour difference has been examined in small, representative regions to establish whether any changes have occurred to particular pigments or pigment mixtures. This analysis indicates that there are no significant changes in colour that can be attributed to colour alterations in the painting. In particular the cushion to the right of the painting, which contains
a red lake pigment, shows no fading. This is reflected in the overall darkness of the difference image.

There are, however, some light areas in the difference image. Five common sources for these features have been identified:

1. The accuracy of the type 2 transform has limits, so that some small differences due to image misalignment are observed; these features generally occur along high contrast edges, so their source is usually obvious.

2. At the left and right edges of the painting are regions of greater difference. This painting has an integral frame and shadows from the light sources are inevitable. Slight differences in lighting in 1993 and 1999 are responsible for these ‘shadows’.

3. Slight differences in the lighting angle can create specular reflections in one of the images. These appear as very light areas in the difference image, for example at the edge of the fabric hanging above, and to the right of the Virgin’s head.

4. Small dust particles or fibres attach themselves to the painting or are lost during time, which show up as changes in the difference image.

5. Optical flare has already been identified as a major factor when comparing images made with a digital camera [14]. Although not apparent in the difference image for *The Virgin and Child in an Interior*, problems with flare were noticed when making the image comparison for *The Adoration of the Kings* by the Master of Liesborn.

The results presented here confirm that flare, shadow and gloss must be considered carefully during image acquisition. Since the interim study that highlighted the problems of flare, measures have been taken to eliminate this effect, using an extra calibration step. The images made in 1993–95, used for comparison here, were made before this additional calibration was available, rendering direct comparison of the dark areas of some of the paintings more difficult. In the future, comparisons between flare-free images should make colour difference assessments more straightforward. Although no significant colour changes have been detected in the paintings examined to date, a programme of continuing measurement is in place.

**Transportation damage**

Another core objective in building the VASARI scanners was to allow images to be made before and after paintings were transported to exhibitions. A general description of the methodology used in these studies has been given elsewhere [3]. These first applications showed that the technique had great potential for detecting alterations in the condition of paintings under study. Works of art by Kirchner, Sisley, Memling, Marc, Degas and Nolde have already been monitored [16–18]. Here we report further case studies, some advances in the techniques employed, and an interim appraisal of our approach.

Compared to the studies published so far, the main technical
improvements arise from the use of the rubber-sheeting algorithm to compare images made before and after transportation, as well as the use of the high-resolution MARC camera to make images of some of the paintings examined. The methods for acquisition and computer-aided comparison, given previously [3], have been made faster, and the technical difficulties experienced during data capture and image processing have been overcome.

The logistics of a comprehensive monitoring programme dictate that not all of the paintings owned by the Bayerische Staatsgemäldesammlungen, Munich, on loan each year (around 400) can be assessed. New case studies are reported in Table 2. The changes noted can be divided into several categories, ranging in severity from loss or gain of dust particles on the painting surface (as found in the colour change study) to displacement of paint particles. Most of the displacements occur at or near the edge of the painting; canvas fibre deformations also occur near the edge of the painting.

As in our colour change study, alterations in shadow and gloss create artefacts that produce differences that are clearly not attributable to physical changes. A more severe problem is that experience suggests that three-dimensional changes, such as blisters and loosening of tiny particles, are hardly detectable. In addition, the application of the rubber-sheeting algorithm improves image registration, but makes it extremely difficult to detect any deformation of the stretcher, and hence of the canvas, that might be caused by transportation or by climate changes. The detection of dust on the surface, here and in the colour change study, is, however, indicative of the overall sensitivity of the methods applied. As pointed out in the introduction, the main advantage of the procedure lies in the computer-aided comparison of two images; the digital techniques are clearly superior to a simple comparison by eye. Physical changes are mainly located at the edges, which confirms our expectations. In Gauguin’s Bretonische Bäuerinnen, the extremely brittle layers may have contributed to the high proportion of changes in the central part of the painting, underlining the risks associated with transportation.

**Improved infrared images**

Since the early 1960s, infrared reflectography has proved itself an invaluable tool in non-destructive investigation of paintings. Major technical improvements to the method were made only in the late 1980s. Some groups focused on replacement of the Vidicon (lead sulphide) detector by solid state infrared-sensitive arrays [19, 20], while we have concentrated on improving the image quality of the commonly-used Hamamatsu infrared Vidicon system by digital image processing. From the outset, it was clear that the VASARI system could play an important part in these technical developments. In Munich, each component of the infrared reflectography set-up was analysed individually [21], leading to the first fully automatic acquisition of a reflectogram mosaic image of a painting by Johann Georg von Dillis. In London, new software was developed to improve the reflectogram mosaic assembly procedure [22]. Following earlier non-destructive spectroscopic differentiation of drawing inks [23–25], a system for multichannel imaging spectroscopy, based on the VASARI scanner, was developed [26–28].

Most effort was, however, devoted to improving the quality of digital infrared reflectograms. In Munich, the signal-to-noise ratio of the Vidicon camera has been improved by cooling the sensor with Peltier elements and by averaging each frame 32 times over a period of around 35 seconds; the resulting signal contains 7.5 bits of information and is digitized to 8 bits. Further corrections compensate for ‘ghost image’ effects of the Vidicon tube, dark current leakage, and inhomogeneity in the lights, optics and sensor, including gamma differences across the sensor surface. Some of these innovations have also been implemented in London.

Geometric distortions, mainly from the sensor itself, but also from the optics and focal plane misalignment, are corrected using the second-order (type 3) transformation described above. In this case, the ‘before’ and ‘after’ images are a synthetic image of a regular grid and the image of an identical grid made with the Vidicon camera under exactly the same conditions that will be used to acquire the infrared reflectograms. The parameters generated by this transformation are applied during the acquisition to correct individual frames. Finally, the lightness of each single frame is adjusted by an iterative process, which minimizes the difference between all the sub-images before the final mosaic assembly is made.

The image acquisition, correction and assembly are fully automated. In addition to storing the infrared data archivally on CD-ROM and DAT (digital audio tape), black-and-white photographic negatives are made from the digital information. Negatives and life-size prints have been made of the infrared reflectograms of some paintings to assist in art-historical study, technical examination and conservation treatment. For books and catalogues, infrared reflectograms can be reproduced either from the photographic negatives or directly from the digital data (Fig. 3). Recent examples include monographs on Lucas Cranach the Elder [29, 30] and Albrecht Dürer [6], and a catalogue of fifteenth-century Netherlandish paintings [31].

**Conservation documentation**

As a side-effect of long-term colour measurement and condition assessment before and after transportation, paintings are being
Fig. 3 Digital infrared reflectogram of Die Heilige Familie mit Johannes dem Täufer, Elisabeth und zwei Engeln by Andrea del Sarto (portfolio, 137 × 104cm, Bayerische Staatsgemäldesammlungen, Munich Inv. No. 501). The image consists of 375 sub-images; for further details of the experimental conditions see [51].
imaged colorimetrically at a resolution of around 15 pixels per millimetre. These digital VASARI or MARC images can replace conventional photographs and may be exploited for other purposes. From a preventive conservation point of view this is an important spin-off, as their permanence reduces the number of occasions on which paintings, particularly those that are in greatest demand, need to be taken off display for photography and exposed to the risk associated with unframing and transportation within the museum.

High-resolution images are also being made of paintings at each stage of a conservation treatment. These not only provide an irreplaceable and immutable record of the state of a painting before cleaning, but also allow comparisons to be made between colour before and after cleaning [32]. Figures 4a and 4b show corresponding details from the high-resolution images of The Virgin and Child by Jan Gossaert (National Gallery, London, No. 1888) acquired before and after the recent cleaning that revealed this painting to be the work of Gossaert, rather than a seventeenth-century copy as had been thought previously [33]. The image of the painting before cleaning provides evidence of the disfiguring craquelure that led to the misinterpretation of its age; this is particularly obvious in the flesh-coloured passages. The image in Figure 4b has been re-sampled using the rubber-sheeting technique so that it coincides exactly with that in Figure 4a. These two images can therefore be used to produce a colour difference image, using the same technique as applied to images when assessing long-term colour change. Figure 4c illustrates this colour difference image. The dark areas indicate that little or no colour change has occurred, while the white areas indicate changes in colour during cleaning. Changes due to the removal of the old varnish and craquelure can be seen. Particularly striking are the white areas on the Virgin’s shoulder, where part of her garment was previously obscured, and in Christ’s outstretched hand, whose gesture had been altered in an earlier restoration.

CONCLUSIONS
The VASARI and MARC projects have led to the production of permanent, accurate, high-resolution digital images suitable for a number of conservation-related and archival programmes [34–36]. The quality of these images, combined with type 2 transformation algorithms, has allowed the condition of paintings to be compared before and after conservation treatment, transportation on loan and long-term display, as well as improving the quality of infrared reflectogram mosaic images. By virtue of their high resolution and excellent colour quality, MARC images have also been used in publishing catalogues and prints; the first of these was a catalogue of Flemish Baroque painting [37]. Technical details of the methods used for colorimetric printing of digital images have also been published [38–40]. More recently, we have used calibrated, large-format printers to produce colour-accurate life-size prints of paintings to act as reference images during conservation treatment, a programme that will be described in more detail in due course.

ACKNOWLEDGEMENTS
The VASARI and MARC projects were partly funded by the European Commission (ESPRIT Nos. 2649 and 6937). Work in Munich on imaging spectroscopy and infrared reflectography has been funded by the Bundesministerium für Forschung und Technologie (03-B39/NUE). Studies of colour change in London have been supported by an external grant from Hewlett Packard Laboratories. We acknowledge the support of our many colleagues in the VASARI and MARC projects, many of whom appear in the reference list.

REFERENCES