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Colour Change Measurement by Digital Image Processing

David Saunders

Introduction

The detection and measurement of colour change in paintings has been the basis of many research projects within the Scientific Department over a period of some years. The aim of this work has always been to prevent such alteration by early identification of potential hazards. A reflectance spectrophotometer, specifically designed and constructed for use in this department, has been in use to detect and measure long-term colour changes since the mid-1970s. In addition to this long-term colour permanence experiment [1,2], the equipment has been used to measure colour changes which result from conservation treatments [3] and by the accelerated photodegradation of certain pigments.

Despite the wide range of applications for which the reflectance spectrophotometer has proved suitable, there remain a number of problems associated with the use of this method of monitoring colour change over a long period. Amongst the most serious of these is the necessity to select the set of points on the painting surface which are to be measured at the start of the experiment. Clearly, a limited number of areas must be chosen for study when the painting is first examined. This limit is imposed by the time taken to reposition accurately the optics of the apparatus for a subsequent measurement. Realistically, it is not possible to monitor more than twenty points on the surface of each painting. The colour measurement at each point covers an area of approximately 0.12 cm^2. Even with judicious selection of those portions of the painting most likely to provide evidence of colour change, only a fraction of the painting surface is included within the total area measured.

Whole painting recording

Photographic densitometry

One technique which was explored in an earlier attempt to measure colour over the whole surface of the painting was photographic densitometry. This method had already been used with some success to elucidate the layer structure of paintings by an examination of X-ray negatives [4].

To record colour, a procedure was developed by which 35 mm black-and-white negatives corresponding to the whole painting photographed through appropriate colour separation filters were made. By including on each negative a set of ceramic reflectance standards it is theoretically possible to compare records made at different times and hence to detect colour changes. In reality this system is fraught with difficulties. Firstly, there is no method of ensuring either uniform lighting of the object or even development of the negative. Secondly, assuming it were possible to achieve comparable negatives, there was no rapid, simple optomechanical method by which a comparison between precise points on the two negatives might be made.

By the end of the 1970s it was suggested that despite the absence of a suitable apparatus to achieve this comparison between negatives, a set of colorimetric negatives should be made for some paintings [5]. This set would comprise exposures made through standard red, blue and green filters, the transmission of which could easily be checked, and a whole spectrum (panchromatic) exposure. Each negative would be recorded under standard lighting conditions and an exposure of a blank card would be made to record evenness of illumination. The future development of an appropriate system would allow these negatives to be compared with others recorded under similar conditions at a later date. The problem of uneven development could not be overcome. A project to make a colorimetric photographic record of each painting measured using the reflectance spectrophotometer was proposed [6], but subsequent advances in digital imaging techniques resulted in a different approach to whole painting colour measurement being adopted.

Digital recording

The limitations of photographic methods for recording colour prompted the investigation of optomechanical scanning devices as a means of creating a permanent record of colour. A feasibility study conducted in 1973 concluded that whilst the equipment required to scan the painting mechanically at a resolution of four lines per inch existed and that it would be possible to convert colour information into a digital form, no mass storage device with sufficient capacity was then available [5]. Even if sufficient storage capacity had been commercially available, the difficulties in ensuring positional accuracy of every part of a painting when there are expansions and contractions would have been considerable. As imaging technology developed, making a record of the entire painting using a single sensor device became possible. Solid state TV cameras were thought to be the most suitable devices for whole painting imaging.

In 1977 it was noted that an imaging chip with an array of 185,440 (380 × 488) charge-coupled sensor elements was available and that a TV camera containing such a charge-coupled device (CCD) might be used to measure reflectances from a painting and from a white card, the latter reflectances being used to calibrate the measurements made upon the painting [7]. The major problem of any image processing system still lay in the manipulation and storage of the large volume of image data that would be generated. The departmental Wang computer described in the first issue of this *Bulletin* had a 16K central processor chip [8]. This effectively limited the size of image which could be stored to 32 × 32 data points. To record in three colours would require three 16K storage chips [7].

When a system to record and store images digitally was eventually purchased in 1982 it was based not upon a solid state CCD camera but upon a conventional and less expensive monochrome TV camera, a digitizer and a DEC computer with greater storage capacity than the Wang. This equipment was intended as a prototype to allow problems of image acquisition, calibration and comparison to be tackled whilst awaiting improvements in CCD camera technology.

Digital image processing: principles

Before discussing the prototype system which was set up at the National Gallery in the early 1980s some explanation of the principles of digital imaging processing using a conventional TV camera is appropriate.

The vidicon camera in the prototype system, like all other cameras of this type, operates on the raster-scan principle, breaking up the image into a number of horizontal bands. A standard European television picture is made up of 625 such bands (525 in the USA). Each band is transmitted in turn by the camera as a continuously varying voltage, termed an analogue signal. The voltage at a given time corresponds to the brightness of a particular point on the image. When the signal is received by the TV monitor, the 'flying spot' which moves across the bands of the picture darkens or brightens according to the applied voltage, thus reproducing the intensity pattern of the original image. It would be possible to store this analogue signal on magnetic tape using, for example, an ordinary video recorder. In order to make best use of the ability of a computer to store, correct and manipulate the data, it is best to convert this analogue signal to a digital form.

The digitizing procedure is carried out by an analogue to digital converter (A–D converter) which periodically samples the incoming analogue signal and converts this to a numerical (digital) value. The time interval between samples will determine the number of picture elements (pixels) in each of the bands which make up the image. Clearly, the greater the number of pixels, the greater the resolution of the digitized image. For example, Fig.1 shows a monochrome image of a reproduction which has been sampled to give 256 pixels in both the horizontal and vertical directions. Figs. 2 and 3 show the same reproduction imaged to give 64 × 64 pixels and 32 × 32 pixels respectively. Comparison of these images illustrates the increase in resolution made possible by a higher sampling frequency. The improved resolution must be judged against the increased size of the central processor unit (CPU) and mass storage device needed to cope with higher resolution images if they are then transferred to a computer for processing. In this example the image shown in Fig.1 will require 64-times more storage space than that shown in Fig.3.

The absolute resolution, in terms of pixels per centimetre (or some similar unit), will depend not only upon the sampling frequency but also upon the distance between the imaging device and the painting. By reducing this distance it would be possible to double the absolute resolution. The resulting image would, however, only cover one-quarter of the area encompassed by the original.

The analogue signal entering the A–D converter can have any value between zero and the maximum output voltage of the camera. But, the digitized information from the sampling procedure is necessarily quantized, with an inevitable loss of information. How much information is lost will depend upon the number of grey levels generated from the analogue signal by a particular A–D converter. The image in Fig.1 has been converted using 256 levels of grey whilst Figs. 4 and 5 show the effect of reducing the number of levels of grey to 16 and 8 respectively. The human eye can only distinguish a certain number of grey levels, but for comparison of digitized images it is preferable to have the maximum information possible. The limits are imposed by computer size and time taken to perform algorithms upon the data. For example, the image in Fig.1 comprises 256 × 256 pixels each bearing a grey level value between 0 and 255. The image in Fig.6, which is just about recognizable as a representation of the original reproduction, shows the effect of reducing both the number of pixels and number of grey levels. It is made up of 64 × 64 pixels each bearing a value between 0 and 7.

The prototype system

The equipment acquired to begin investigations into the digital recording of colour was based around the vidicon camera and the need to convert its analogue output to a digital form for image processing. This conversion was achieved using a Gresham-Lion 'digivisor', which passed the digitized data directly into the CPU of the DEC LSI–11 computer controlling the system [9]. The sample frequency was selected to give an image comprising 256 × 256 pixels. This was held in the CPU as an array or matrix which could be treated mathematically to calibrate, correct or enhance the image. The analogue signal was digitized to one of 256 values. The choice of grey levels between 0 (black) and 255 (white) allowed a pixel value to be stored in a single byte of computer memory, each complete monochrome image occupying 65,536 bytes. This image could be transferred from the CPU to a magnetic disc for more permanent storage.

The choice of magnetic disc was dictated by the wide availability of these storage media at the time that the procedure was devised. It was known that magnetic discs might not be the most permanent archiving method in future years but that the data could be transferred to an improved medium at a later date [10].

To detect changes in colour the painting was imaged through three standard colour separation filters [11]. Each image was converted to a digital form, corrected and stored separately on disc. Neither this system nor subsequent equipment was designed to produce images which might be recombined to give a true colour image.

In order to display an image on the TV monitor the information from the CPU had to be passed through a digital to analogue (D–A) converter. This was achieved

Figure 1 A digitized image of a reproduction of Luis Meléndez, *Still Life with Oranges and Walnuts* (No.6505). This image comprises 256 × 256 pixels and is digitized to 256 grey levels.

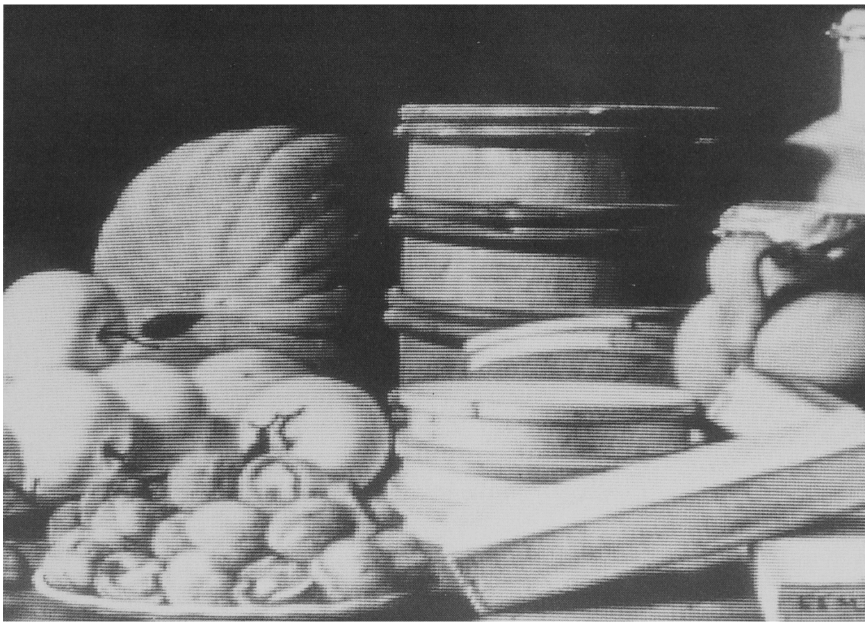


Figure 2 Image of the same reproduction as shown in Fig. 1, but comprising 64 × 64 pixels digitized to 256 grey levels.

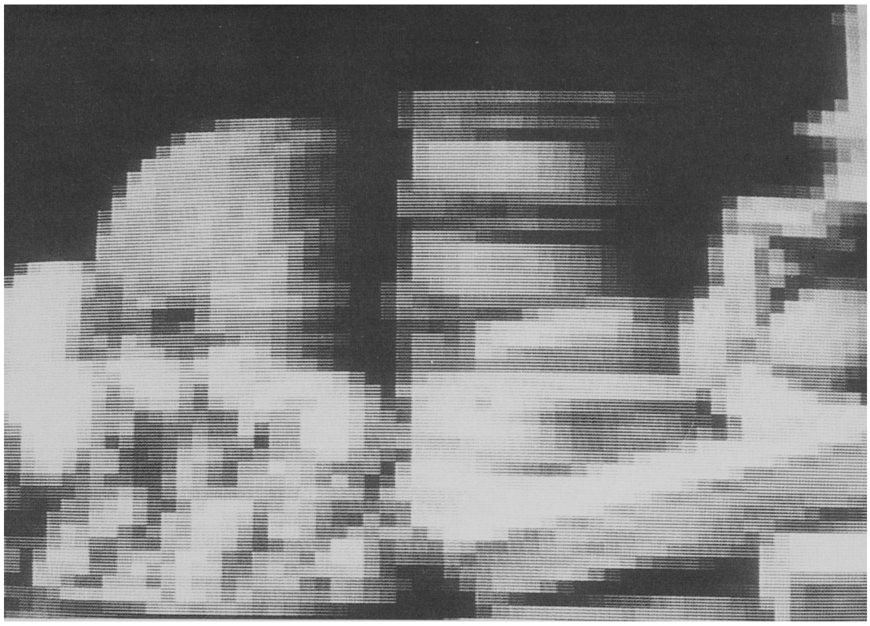
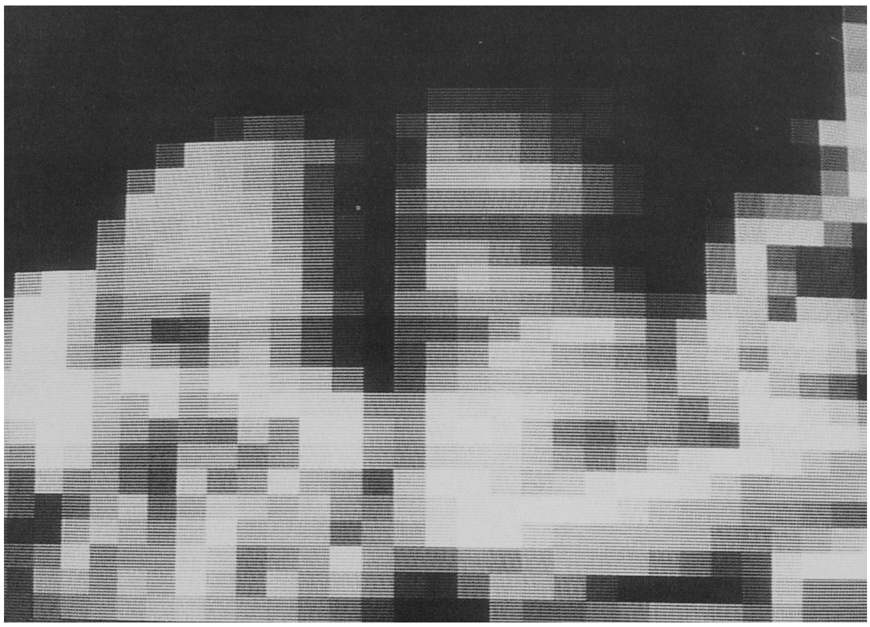


Figure 3 Image of the same reproduction as shown in Fig. 1, but comprising 32 × 32 pixels digitized to 256 grey levels.



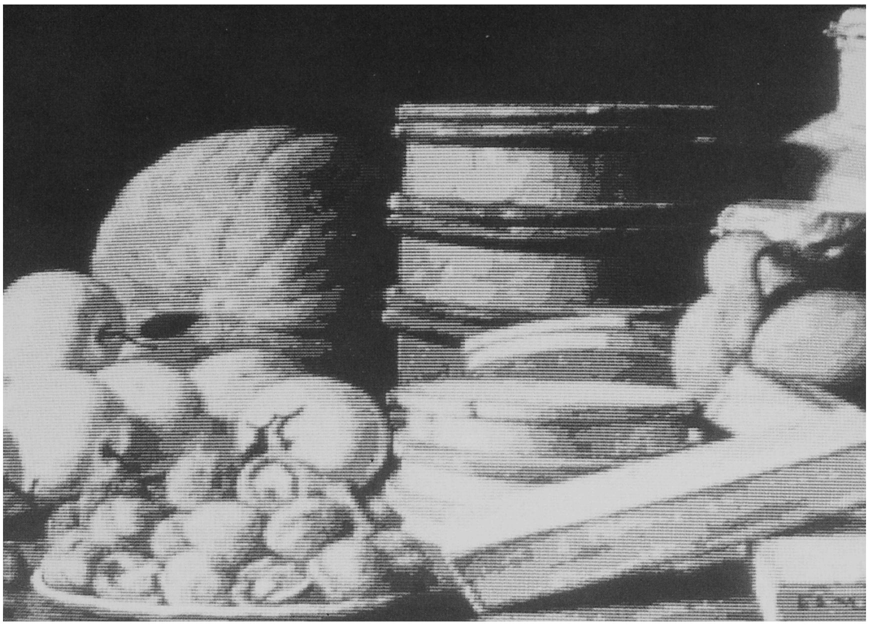


Figure 4 Image of the same reproduction as shown in Fig. 1, but comprising 256 × 256 pixels digitized to 16 grey levels.

Figure 5 Image of the same reproduction as shown in Fig. 1, but comprising 256 × 256 pixels digitized to 8 grey levels.

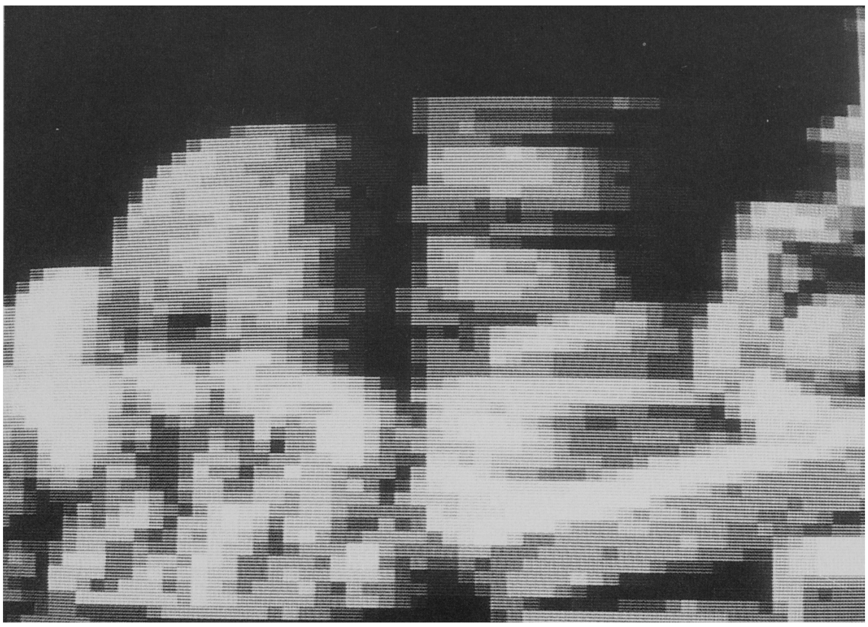


Figure 6 Image of the same reproduction as shown in Fig. 1, but comprising 64 × 64 pixels digitized to 8 grey levels.

using the Gresham-Lion 'supervisor' which converted the corrected digital to an analogue signal compatible with a standard TV monitor. The 'supervisor' could be programmed to generate false colours either to enhance the image or to draw attention to areas where a difference between two images had been detected. The prototype system is shown schematically in Fig.7.

The measurement procedure

Before the three colour separation images were made, the painting was positioned in a plane perpendicular to the focal axis of the camera. If the purpose of the recording procedure was to make another measurement on a painting that had already been studied, exact superimposition of the new and old images would be required. It is possible to record the images without ensuring accurate repositioning and then to make positional corrections to one of the stored images. Software to move the image by units of one pixel in the horizontal or vertical direction is relatively simple, whilst skewing of the image requires more complicated software. It is preferable, therefore, to record images with an exact pixel to pixel match. Fine adjustment of the position of the painting using a mechanical easel whilst comparing old and new images was found to give a repositioning accuracy better than could be achieved by software correction [10]. Indeed it was, and still is, believed possible that the technique may yield information on how paintings distort with time.

To achieve suitable illumination, the painting was then lit from an assembly of lamps on a movable frame; the frame can be seen in Fig.8 which illustrates the prototype system in use. The lighting was positioned so as to be at an angle of approximately thirty degrees from the picture plane. This angle ensures that the image is not subject to specular reflections and that the surface texture of the painting is not exaggerated by raking light. Since the illumination over the painting surface will not be uniform, a correction must be made to each of the colour separation images before they are stored. This was achieved by replacing the painting by a uniform white matt surface, storing its image and making a pixel by pixel correction. Finally, the corrected colour separation image was stored on magnetic disc.

The colour filters were regularly checked for deterioration by recording their transmission spectra. A set of National Physical Laboratory coloured standard ceramic tiles were periodically imaged using the system. This procedure was designed to give an indication of any change of spectral response by the camera/filter combination or of a change in spectral power distribution of the lamps. The colour calibration procedure will be discussed in more detail in a later section.

Once a corrected image had been stored, it was then possible to make a comparison between the new and old images. Image subtraction provided a rapid method of comparing the two images by creating a map of image difference. The false colour generation facility could then be used to produce an easily interpreted indication of areas where change had occurred. Another method developed to compare new and old images was to display each upon the screen in rapid succession. Any differences between the two images produced a flicker. These procedures were intended to form part of a software package that would first detect and then measure colour difference. The latter part was never developed fully since it became obvious that the ability of the system to measure colour accurately was severely limited by problems with the vidicon camera.

Limitations of the prototype system

The vidicon camera had always been intended as a temporary solution whilst awaiting the purchase of a CCD camera [12]. Within a year of setting up the prototype system it had become clear that little more could be achieved without a CCD camera. The vidicon camera was not designed for photometric measurements. Its noise level was too high, even when several images were acquired and averaged. The response of the device was also non-linear. Finally, the dimensional stability of the image was uncertain, making effective superimposition difficult.

In addition to the problems with the camera, the computer was prone to failure and lacked sufficient CPU

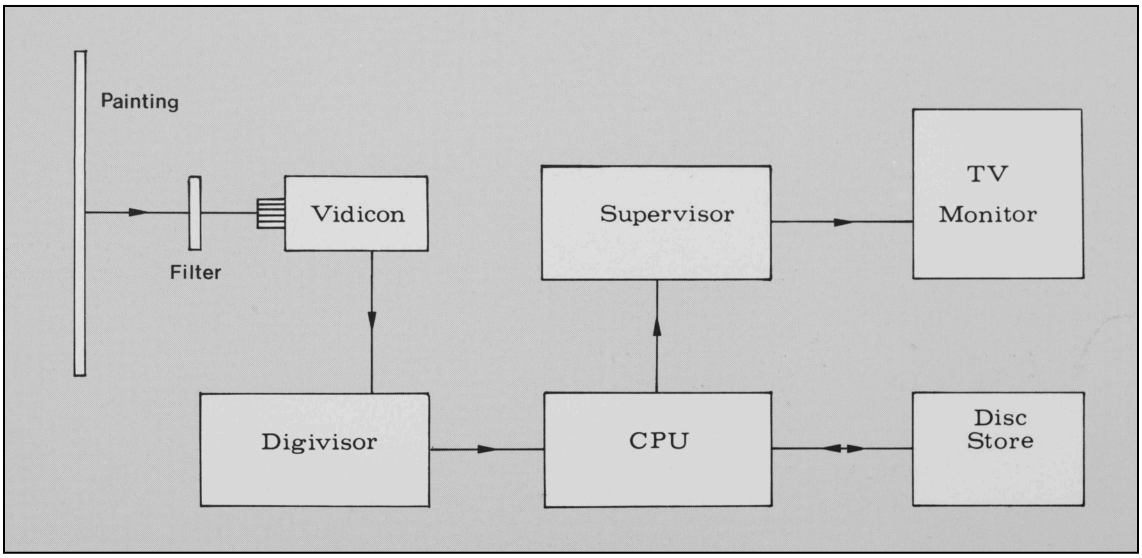


Figure 7 Schematic representation of the prototype system.

space to allow whole images to be manipulated. Each image had to be retrieved from store for display in eight segments, whilst any procedure which involved comparison of two images had to divide the data into sixteen portions for processing and display.

The current system

Camera

The image processing system purchased to replace the prototype equipment is based upon a solid state camera. A CCD or CID (charge injection device) camera of this type contains a silicon chip which is divided into a large number of rectangular elements. Each of these elements is in itself a photodetector, which accumulates a charge proportional to the number of photons which fall upon its surface during the measurement period. This direct relationship between signal and incident light overcomes one of the main problems of the conventional camera, namely non-linearity. An image is focused onto the surface of the sensor using a conventional camera lens. The nature of the silicon chip ensures that the image is not subject to geometric instability.

At the time of writing, area array CCD cameras are available with up to about 1,400,000 photosensitive elements [13]. Another type of camera contains a linear array 4096 pixels in length which can be moved across the focal plane by a stepper motor to 5200 positions. The resulting image is divided into approximately 21,300,000 pixels [14]. When the camera for the current system was purchased 512 × 512 area arrays or 2048

Figure 8 The prototype system in use. The painting under study is held on the mechanical easel and lit from lamps on the movable frame. In the centre is the vidicon camera and to its right are the 'digivisor' (on top of the TV monitor), the 'supervisor', the computer terminal and disc drive.

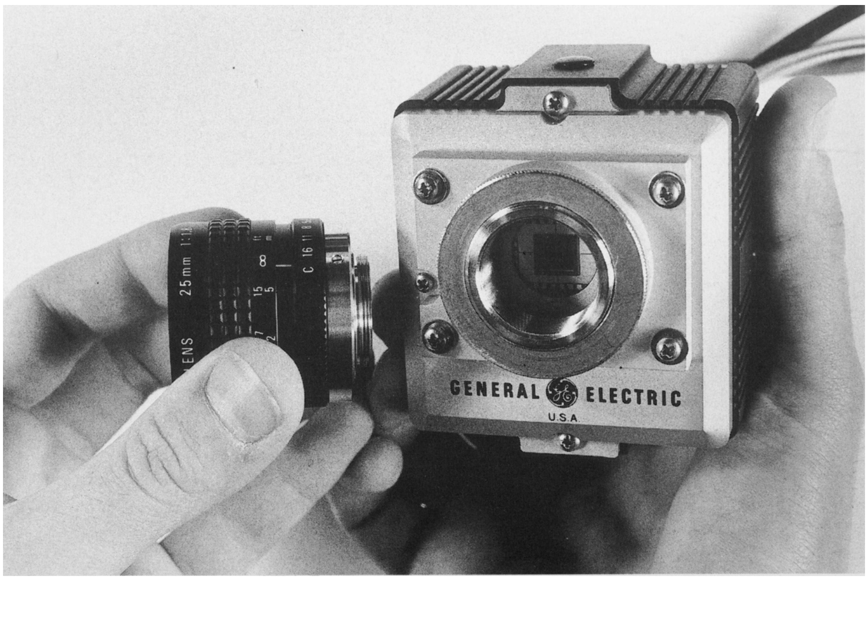


Figure 9 The General Electric TN2509 camera. The lens has been removed to show the photodetector chip beneath.

linear arrays were available. One reason for the eventual choice of a more modest 256 × 256 area array was the data processing capability required to deal with image matrices. A 512 × 512 CCD would have generated four times more data than the device now in use. Should it ever be necessary to make an image of a greater area without loss of resolution it would be possible to create a mosaic from the individual digitized images. This method has already been used to create mosaics from infra-red reflectogram images [15].

The camera selected was a CID camera manufactured by General Electric [16]. This device gives a linear response over a satisfactory range of illumination and has good sensitivity throughout the visible region of the spectrum. The General Electric TN2509 camera is illustrated in Fig.9.

Frame store

Many solid state devices are designed to be used in conjunction with standard TV equipment. As a result the output generated by the camera tends to be a composite video signal compatible with an analogue TV monitor. Whilst this is satisfactory for many applications, it is somewhat self-defeating to have an A–D converter apply another sampling frequency to the signal from the camera which already operates on its own time-base. To overcome this problem an A–D converter was required which would not only convert the voltage of the incoming signal to a digital value but also provide the same time-base for camera operation.

The 338VP frame store used in the current system was specially commissioned to fulfil these functions [17]. This unit provides the power supply for camera operation and also a set of signals to control image transfer from the CID to the frame store. These signals are most important since they ensure the direct pixel mapping of information from the camera to the frame store. A third connection between the two devices carries information from the camera to the A–D converter, where the 256 × 256 image is digitized to 256 grey levels for transfer to the CPU of the controlling computer.

The frame store also acts as an interface between the CPU and the TV monitor by producing an analogue signal from the digital data output by the computer. Alternatively, the frame store can operate in 'live' mode, displaying a constantly updated image from the camera. At any time an image can be 'frozen' and transferred across a parallel interface to the CPU. All functions of the frame store are controlled by the computer through the same interface. The current system is represented schematically in Fig.10.

The frame store effectively performs the functions of both the 'digivisor' and the 'supervisor', in the prototype system. The frame store is not able to generate false colours in the same way as the 'supervisor', so a separate false colour generator is used. This device can be programmed with twelve preset palettes to enhance the monochrome signal from the frame store [18].

Computer

Although the DEC LSI–11 computer could have been used in conjunction with the new camera and frame store, considerable modifications would have been required to overcome the problems associated with limited memory space. In the period between deciding to acquire a solid state camera and its delivery, the department had purchased a Hewlett Packard 9836A for general computing [19]. It was decided that this machine would be adapted to control the image processing procedure. This required the installation of some extra memory (RAM) in order to accommodate the large data matrices for several images. In particular, the capacity to hold three images in the CPU allows two image matrices to be compared and the result to be stored in a third matrix.

Communication between the computer and the frame store was achieved using the standard parallel interface on the HP9836A computer. To allow rapid access of image data not held in the CPU, a 10 MByte hard disc unit is linked to the computer. Data on the hard disc can be read into the CPU in about four seconds. The hard disc is used to store data during image acquisition, correction, processing and comparison. For more permanent storage image data are transferred onto 3.5 inch magnetic discs.

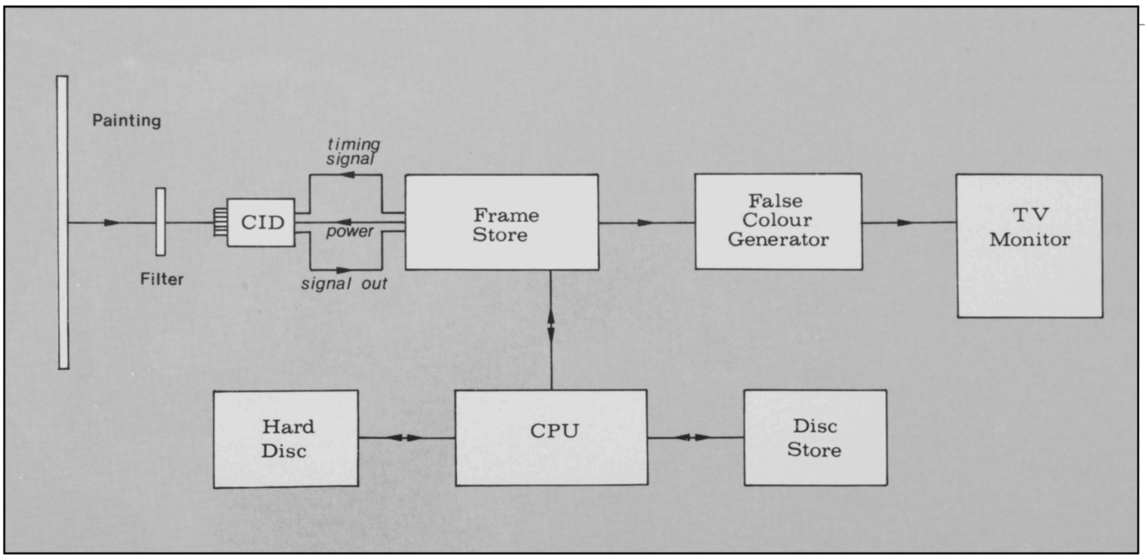


Figure 10 Schematic representation of the current system.

Colour measurement

At this point it is important to differentiate between colorimetric measurements made from imaging the painting itself and the trichromatic scanning of intermediate colour transparencies. Whilst the latter technique may be quite suitable in the reprographics industry and has even found an application in determining colour matches for restoration [20], it is not appropriate for the detection of colour change, since it relies upon the intermediate photographic process with its attendant problems.

The present CID camera, like the vidicon before it, is a monochrome device. In order to measure colour it is necessary to make use of a series of colour separation filters. The response of the camera will depend upon a number of factors; the spectral sensitivity of the photodetector, the transmittance of any filters used, the spectral power distribution of the light source employed and the reflectivity of the object being imaged. It is the last of these that we wish to measure in order to detect colour change. It would be possible to measure the reflectance of the painting at a series of wavelengths across the visible region of the spectrum by using a set of narrow band interference filters. Alternatively, conventional red, green and blue broad band filters might be employed. The advantage of the former technique is that more precise spectral reflectance information is acquired. The disadvantages are that the low transmittance of the interference filters leads, to a decreased signal to noise ratio, and that since the painting must be imaged through each filter in turn, the measurement procedure is lengthened and the amount of data to be stored is considerably increased. We have chosen to use three Wratten colour separation filters and to measure their absorbance curves regularly to detect any changes. The paintings are illuminated using tungsten photographic lamps. To assess any changes in the spectral response of the camera and/or spectral power distribution of the lamps a set of standard coloured ceramic tiles are periodically imaged through the colour separation filters. Any marked difference in measured reflectivity may be attributed to a change in one of the above factors.

The spectral sensitivity of the camera was measured before delivery and is shown in Fig.11. It can be seen that the photodiodes respond not only to light in the visible region of the spectrum but also to infra-red radiation up to about 1100nm. In the future it might be interesting to utilize this infra-red sensitivity, but for the current project it is necessary to use an infra-red blocking filter in conjunction with each colour separation filter [21].

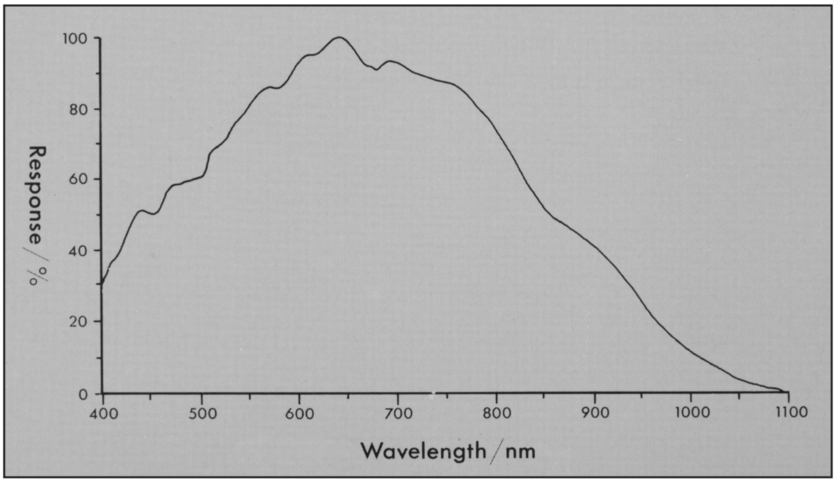


Figure 11 Spectral sensitivity of the TN2509 sensor. The response is expressed as a percentage of the maximum response.

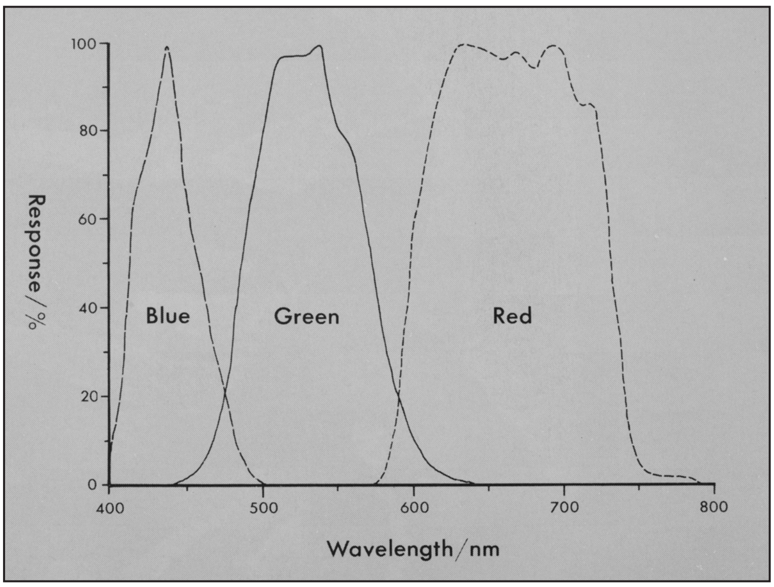


Figure 12 Spectral response curves of the TN2509 sensor through the red, green and blue filter sets. In each case the coloured filter is used in conjunction with an infra-red blocking filter. Each of the curves expresses response as a percentage of the maximum response for that filter set.

The resulting spectral response curves for red, green and blue filters are shown in Fig.12.

The response of the camera through each filter combination when imaging a painting can then be compared with the response produced when imaging a reflectance standard through the same filters. The reflectance standard is a piece of neutral grey card of known lightness. Each response needs to be corrected to account for the signal produced by the camera in the absence of any illuminant, the so-called dark current. Because the reflectance standard is imaged under the same conditions of illumination as the painting, the correction procedure compensates for uneven lighting. The result of these calculations is a set of three colour coordinates, C_r, C_g and C_b, which for an individual pixel are derived as follows:

$$C_r = ((P_r - D) \times Q)/((S_r - D) \times 100) \quad (1)$$

$$C_g = ((P_g - D) \times Q)/((S_g - D) \times 100) \quad (2)$$

$$C_b = ((P_b - D) \times Q)/((S_b - D) \times 100) \quad (3)$$

P = camera response imaging painting

S = camera response imaging reflectance standard

$_{(r,g,b)}$ refer to imaging through the red, green and blue filter sets

Q = lightness of reflectance standard

D = dark current

These colour coordinates do not correspond to any standard system of colour measurement since they are not based upon recognized response curves. They do, however, provide a self-consistent measurement of colour change suitable for the purpose of this research.

Measurement procedure

Image capture

One of the most difficult parts of the measurement procedure is the exact repositioning of the painting in front of the imaging device. This relocation is essential to obtain a pixel for pixel match between old and new data for image comparison. Experiments with the prototype had indicated that exact physical repositioning was preferable to software manipulation as a means of achieving superposition [10].

Several software routines have been developed to assist physical relocation of the painting using the mechanical easel. All require the intervention of the user, no interactive link exists between computer and easel. To reduce the number of possible variables in relocation, the camera to object distance is recorded at the time of the first measurement. This distance is determined by the size of the painting to be imaged and the camera lens used, although for very large works several images may be made in order to avoid further increase in the area covered by each pixel. The painting is then mounted on the mechanical easel. Paintings are by nature not geometric objects, but an attempt is made to align the edges of the painting's support with the easel's horizontal struts. Movement in the horizontal and vertical plane is then used to relocate the painting. For coarse repositioning the method of alternately displaying two images is quite satisfactory. This technique had been used in the prototype system to detect small differences between two images which were revealed by a flickering of the appropriate area of the image. When this method is used for repositioning, the computer causes the stored image of a painting to be alternated with the 'live' image from the CID camera. The painting is manoeuvred so as to minimize the 'shift' between images.

For fine adjustment a second procedure is employed. Initially, the computer performs a subtraction of the matrices corresponding to the live and stored images. The resulting matrix is then combined with a matrix representing a uniform mid-grey. This produces a map highlighting areas of near superposition which is displayed on the monitor. Near superposition appears as a light or dark 'shadow' at the boundary between areas of differing lightness. When the two images coincide precisely the 'shadows' disappear. The technique is

Figure 13 Image of a reproduction of *A Woman*, ascribed to Robert Campin (No. 653b). This stored image was used to illustrate the repositioning routine, see text, Fig. 14 and Plate 12 (p.57).

illustrated in Figs. 13 and 14. An image of a reproduction of *A Woman* ascribed to Robert Campin (No.653b) is shown in Fig.13. This image was stored and used to reposition the reproduction with respect to the camera. Fig.14 shows how near superposition of two images would be seen on the TV monitor. False colour generation enhances the interpretation of the light and dark 'shadows'. Plate 12 (p.57) is a false colour representation of the information in Fig.14. In general the area of a painting covered by a single pixel is large with respect to vibration of the object during imaging. Because of this it is not necessary to employ some of the more elaborate precautions required when imaging small areas at high resolution [22].

Once the painting has been positioned correctly the light sources are adjusted to give suitable illumination. The same restrictions apply to lighting angle as with the prototype. Although subsequent correction software will adjust the image to compensate for uneven lighting it has been found best to aim for reasonably uniform illumination before the image is made.

The procedure for imaging is controlled by the computer and allows the colour separation and calibration images to be acquired quite rapidly, leaving the correction and processing to be carried out at leisure. The efficiency of data acquisition is quite important. Firstly, the painting must not move with respect to the camera between making the different colour separation images. Secondly, the reflectance standard must be measured under the same lighting and camera aperture conditions and, finally, the painting should not be exposed to the considerable illumination required for imaging for any longer than is necessary. The longer the procedure, the greater the chance that a light fitting will be knocked out of alignment or, worse still, that a lamp will fail. Care must be taken not to disturb the camera alignment when changing the filters. The normal sequence for image acquisition is as follows. Firstly, an image of the painting is made without a filter. This image will be used to reposition the painting when future sets of measurements are made. Next, three colour separation images of the painting are made. Once these have been recorded the painting is replaced by the reflectance standard, which is imaged through the red, green and blue filter sets. Finally, the room is blacked-out and a 'dark current' image is recorded and stored.

To minimize the effect of random noise, each of the stored images is an average of sixteen separate images recorded sequentially. As each image is entered the data are added to a matrix which stores the cumulative pixel values. When all sixteen images have been acquired, the average pixel values are calculated and this matrix is stored on the hard disc.

Image correction

The next stage in the procedure is to correct the colour separation images for uneven lighting and to calibrate the reflectances against the standard. The software recalls one of the colour separation images from the hard disc. The dark current image and the reflectance standard image corresponding to the appropriate filter set are also required. A calculation is then performed which adjusts the value of each pixel according one of equations (1), (2) or (3) for the red, green or blue filter sets respectively. Each value of C_r, C_g or C_b is multiplied by 255 and rounded to the nearest integer. In this way the lightness scale fully occupies the 256 levels of grey available with this system. The calibration of the image with respect to a specific reflectance allows the stored image to be independent of the strength of illumination as well as its distribution. This procedure is repeated for the other two colour separation images. The corrected images are then stored on the hard disc and also on a 3.5 inch floppy disc. The latter provides a permanent record of the images, the data on the hard disc are liable to be overwritten during subsequent work.

Image comparison

There are two purposes for image comparison in this project. The first is to detect changes in colour, the

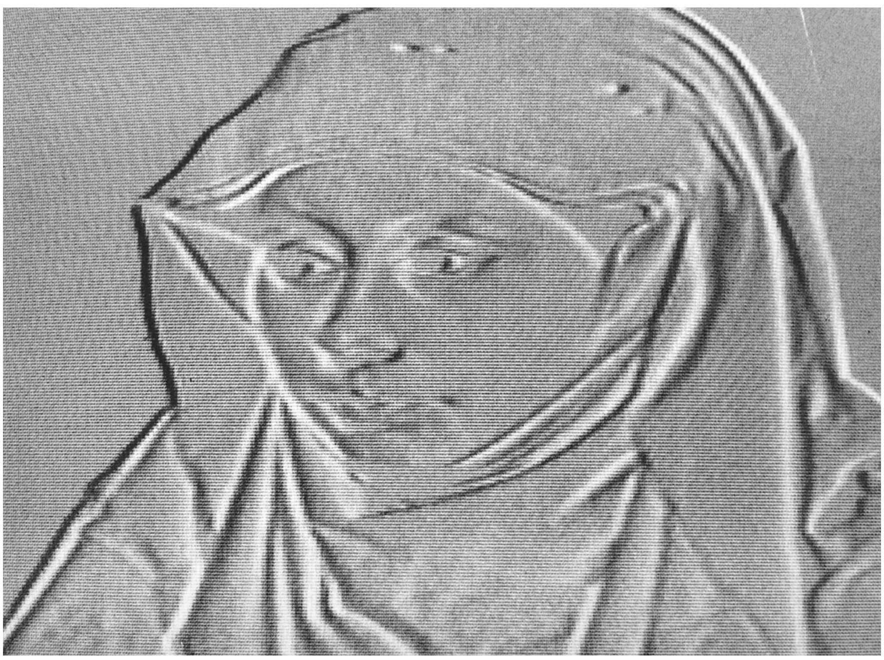


Figure 14 Illustration of near superposition of two images as would be seen on the monitor. The stored image in this case is shown in Fig. 13. See also Plate 12 (p.57), which shows how false colour may be used to enhance the image.

second, and more problematic, is to measure these changes. A number of software procedures have been devised to facilitate the comparison of images. All rely on the prior correction of the data as described above. Colour changes may be detected using a pixel by pixel comparison of images made through the same filter set. The result of this calculation must then be displayed in a visual form. This could be to display simply the matrix produced by subtracting one image from the other, but the differences between the two images may be small and obscured to some degree by random noise. To overcome the problem of noise, a threshold may be set below which differences are ignored. This may lead to some loss of colour change information, but will greatly simplify the interpretation of those changes which remain. After filtering in this way, remaining differences may be enhanced. One approach is to set to 255 the value of all pixels which show a difference. These will then show up as white on black in a monochrome image. This difference map can be superimposed onto one of the images of the painting to give a visual representation of the location of colour change. In this way it may be possible to relate colour change to specific pigments used in these areas.

At the time of writing the project has not been in progress for sufficient time to allow any colour changes to be detected in paintings from the National Gallery Collection. Experiments with reproductions of paintings have yielded some information on the sensitivity of the system. Plate 13 (p.57) shows a detail from Jan van Huijsum, *Flowers in a Terracotta Vase* (No.796). The area of a reproduction shown in this detail was imaged through the blue filter set. To simulate the fading of yellow glazes over blue underpaint, a blue wash was applied to the area of the stem labelled A in Plate 13. To simulate fading of a blue pigment a white wash was applied to the iris petal labelled B in Plate 13. The reproduction was then imaged under identical conditions. Both images were corrected for uneven illumination and calibrated with respect to the reflectance standard. One of the images was then subtracted from the other. The resulting image was then filtered and enhanced. Plate 14 (p.57) shows a false colour map of the changes detected by the image processing system through the blue filter set. The areas of difference are superimposed upon the original image. These areas can be seen to correspond with the deliberate changes indicated on Plate 13 (p.57).

The second purpose of image comparison is to measure colour change in those areas where a difference has been detected. Each pixel can be identified by a horizontal and vertical coordinate. Once a colour difference has been found by comparison of pixel values obtained through one of the three filter sets, the coordinates of that pixel are flagged. The procedure is repeated for each of the three colour separations. The differences in C_r, C_g and C_b are then calculated for each of the flagged pixels. These differences give an indication of the nature of the colour change which has occurred. To assess the magnitude of the colour change the sum of the squares of the individual differences is calculated. In this way, colour change, ΔC, can be defined as follows:

$$\Delta C = ((\Delta C_r)^2 + (\Delta C_g)^2 + (\Delta C_b)^2)^{\frac{1}{2}} \quad (4)$$

Since the value of ΔC is based upon the colour coordinates C_r, C_g and C_b and not upon the standard Commission Internationale de l'Éclairage (CIE) coordinates, $L^\star$, $a^\star$ and $b^\star$, which had been used to express the magnitude of colour changes detected by the reflectance spectrophotometer, it is in no way comparable with the CIE measure of colour difference, ΔE [23]. The factor ΔC does, however, provide a relative measurement of the magnitude of colour change as measured with this system. In the CIE $L^\star$, $a^\star$, $b^\star$ colour space a ΔE of unity is supposed to indicate a just-visible difference in colour [24]. As yet the corresponding value of ΔC has not been calculated for a range of colours. To what extent changes at the just-visible level can be detected depends upon the sensitivity of the system and is the subject of continuing research.

Summary

The current image processing system will be used to acquire colour separation images of paintings in the Collection. It is proposed that these be compared with similar images made at five-year intervals in the future. It is hoped that it will prove possible to relate any colour changes so detected to environmental conditions in the areas in which the paintings have been stored or displayed.

It is most likely that the technology which has advanced so far since the decision to acquire this particular system was taken will develop further. Such improvements may make very high resolution digital images a practical and affordable method of not only comparing colour, but of making a more permanent archival colour record of a painting than is possible by conventional colour photography.

Notes and references

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2. Saunders, D.R., 'The Measurement of Colour Change in Paintings', *European Spectroscopy News*, **67** (1986), pp.10–18.

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5. Thomson, G., Report entitled 'Whole Picture Colour Recording', dated 1 August 1979.

6. Thomson, G., Report to The National Gallery Honorary Scientific Advisory Committee, dated 31 October 1979.

7. Thomson, G., Report to The National Gallery Honorary Scientific Advisory Committee, dated 10 November 1977.

8. THOMSON, G., MILLS, J. and PLESTERS, J., 'The Scientific Department of the National Gallery', *National Gallery Technical Bulletin*, **1** (1977), pp.18–28.
9. The 'Digivisor' and 'Supervisor' units were supplied by Gresham Lion (PPL) Ltd, Twickenham, Middlesex. The DEC LSI–11 computer was supplied by Digital Equipment Co. Ltd, Reading, Berkshire.
10. THOMSON, G. and STANIFORTH, S., 'Identification and Measurement of Change in Appearance by Image Processing', in *Science and Technology in the Service of Conservation*, N.S. Brommelle and Garry Thomson (eds.), Preprints of the IIC Washington Congress (1982), pp.159–61.
11. For all colour separation work Wratten filters No.25 (red), No.47B (green) and No.58 (blue) are used. These filters are manufactured by Kodak.
12. THOMSON, G. and STANIFORTH, S., Report to The National Gallery Honorary Scientific Advisory Committee, dated 9 November 1981.
13. The Videk Megaplus CCD camera contains an area array of dimensions 1340 × 1037.
14. The Eikonix Series 850 camera produces images containing 4096 × 5200 pixels with digitization to 256 levels of grey. The Eikonix 1412 camera gives 4096 × 4096 pixels with 4096 grey levels. Both Eikonix and Videk are divisions of Kodak.
15. WECKSUNG, G., EVANS, R., WALKER, J., AINSWORTH, M., BREALEY, J. and CARRIVEAU, G.W., 'Assembly of Infra-Red Reflectograms by Digital Processing Using a Portable Data Collecting System', in *Preprints of ICOM Committee for Conservation*, 8th Triennial Meeting, Sydney, Australia, Vol.1 (1987), pp.107–110.
16. The camera incorporated in the current system is a General Electric TN2509 solid state device, supplied by Vision Intelligence Ltd (formerly Adrian March Electronics Ltd), Bordon, Hampshire.
17. The 338 VP frame store was also supplied by Vision Intelligence Ltd.
18. The OFA II(C) false colour generator was supplied by Oxford Framestore Applications Ltd, Wantage, Oxfordshire.
19. The Hewlett Packard 9836A computer and 9153 hard disc unit were supplied by Hewlett Packard (UK) Ltd, Wokingham, Berkshire.
20. Digitized images of colour transparencies have been used to calculate 'global colours' for use in retouching large areas of paint loss. The 'global colour' is calculated by extrapolation of the colour in the surrounding area into the region of damage. See CASAZZA, O. and FRANCHI, P., 'Art for the Ages', *Perspectives in Computing*, **5** (1985), pp.4–13.
21. The correlation of features in the visible image with those in either the infra-red, or indeed X-ray, images is of considerable interest. The analogue signal from a conventional Hamamatsu infra-red camera fitted with appropriate filters has been digitized. Subtraction of the visible image from the infra-red image has displayed *pentimenti* and overpainted areas with greater clarity. See 'Riflettoscopia all'Infrarosso Computerizzata', *Quaderni della Soprintendeza ai Beni Artistici e Storici di Venezia*, **6** (Venice 1984).
22. For a description of the procedures adopted in high resolution scanning of very small areas, see CALMES, A.R. and MILLER, E.A., 'Registration and Comparison of Images Obtained at Different Times for Aging Studies of the U.S. Constitution', *Proceedings of the Society of Photo-Optical Instrumentation Engineers*, **901** (1988), pp.61–4.
23. 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).
24. The CIE L^*, a^*, b^* (CIELAB) colour space is not, however, uniform. A consequence of this non-uniformity is that a just-visible difference between two colours in some regions of this colour space may give a calculated colour difference (ΔE) considerably in excess of unity. Several attempts have been made either to modify CIELAB space to achieve uniformity or to adjust ΔE values to account for this non-uniformity. See LUO, M.R. and RIGG, B., 'Uniform Colour Space Based on the CMC(l:c) Colour-Difference Formula', *Journal of the Society of Dyers and Colourists*, **102** (1986), pp. 164–71; and CLARKE, F.J.J., MCDONALD, R. and RIGG, B., 'Modification to the JCP79 Colour-Difference Formula', *Journal of the Society of Dyers and Colourists*, **100** (1984), pp.128–32.