Image Capture and Restoration of Medieval Stained Glass

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Abstract

A project is underway at the church in Fairford, England, to create a high resolution digital image archive of the historic stained glass windows. A combination of film photography and digital photography has been used to capture images of the windows in small sections. Image processing techniques will be used to mosaic these sections into large seamless digital images. A specially-constructed stained glass test panel enables colorimetric calibration. Experiments have demonstrated the viability of digital restoration of detail in the images.

The Project at Fairford Church

Fairford is an attractive Cotswold village in Gloucestershire, England. Its Parish Church of St. Mary was rebuilt between 1491 and 1497, paid for by a wealthy local wool merchant. It is a fine example of the English Perpendicular style and has remained virtually unchanged to the present day. Its glory is the set of 28 large medieval stained glass windows, which, having escaped the ravages of Edward VI's reign and later those of the Puritans, remain the only set in any parish church in the UK to preserve the original medieval glazing scheme intact. The Fairford windows are of exceptional historical significance, having been made by the circle of largely Continental glaziers settled in South London in the closing years of the 15th Century and increasingly attracting the patronage of the Crown and Court. The same workshops also produced the windows of Westminster Abbey and King's College Chapel (Cambridge) a few years later. It has even been suggested that the windows at Fairford were endowed by Henry VII and that they contain 'hidden portraits' of the royal family and courtiers.[1]

Fairford is approaching its quincentenary, which will be celebrated in June 1997. As part of this activity a project is underway to create a digital image archive of the images in the windows and subsequently to publish a book and CD-ROM which explain the significance of the windows. CD-ROM provides an ideal vehicle for a multi-thematic, multimedia presentation, exploring various themes based on material from the book by linking the images of the glass together in different ways, such as:

- A catalogue of the windows and their images;
- Restoration of the glass, including cleaning and removal of repair leads;
- Place in the development of stained glass fabrication techniques;
- Spiritual and religious significance of the images;
- Associations of the images with Henry VII and his court;
- Evidence of the society and times of late medieval England *c.*1500;
- The regional context-geography and culture of the Cotswolds;
- A bibliography and set of references for further investigation.

The treatment of these themes will be on at least two levels: one a 'general interest' level for the lay person and the other as a resource for the serious researcher who wishes to make an in-depth study. The multimedia format allows various types of material to be included, such as: static images of the glass itself; layered images, showing restoration/reconstruction of the designs on the glass or superimposed faces of the glass and royal portraits; moving images, such as video clips of the conservationist at work or film excerpts; narration, including experts talking about the subject; atmospheric sounds, such as church music; graphics, such as diagrams and plans; and text, including annotation of images and descriptive notes.

The project at Fairford is important, not only because of the special national heritage significance of the windows, but also because it provides an opportunity to demonstrate in a media-friendly way the convergence of art, science, cultural studies and digital imaging technology.

Photography of the Stained Glass Windows

A complete photographic survey of the stained glass windows was performed, using Fujichrome transparency film in two formats: a large-format 5×4" plate for each complete window, using a Sinar camera with natural daylight, augmented by interior flash light to add definition to the surrounding stonework; and a series of sectional views of the glass panels on medium-format 6×7 cm roll film, using a Mamiya camera with a tungsten backlight. On completion of the project, the final set of photographs will be lodged with the archives of the National Monuments Record Centre for future research and conservation purposes.

Several of the windows were also imaged directly with a high resolution digital camera, the Kontron *ProgRes 3012*. The camera was mounted on a tripod, moved to successive positions of the window and held stationary while each image frame was captured. With a 25mm lens, the camera was positioned about 150 cm away from the plane of the glass so that there was no physical contact and no danger of damage to the windows. The camera's internal scanning process takes 16 seconds to generate a high resolution image frame, transferred to the host computer by an 'umbilical' cable and processed by an 'Acquire' plug-in module to Adobe *Photoshop*.

The normal reliance on external daylight for illumination of the windows was considered to be unsatisfactory for this application for various reasons: (a) the great variability in intensity, direction and colour balance of daylight; (b) the shadows that may be cast onto the windows at some times of day by external structures; (c) rapid changes in intensity, due for example to cloud movement, which could occur within a 16-second digital scan period; and (d) the partial transparency of the glass, which in many cases results in visibility of the background. The last of these problems can be solved by hanging a white sheet at a suitable distance behind the window, but this doesn't overcome the others. The ideal external weather conditions for photography of stained glass windows are a bright overcast day with dense fog cover, to give perfectly diffused and uniform white light.[2] Unfortunately such conditions are difficult to produce to order.

Experiments were conducted to determine a method of illuminating the windows from the outside, to produce the best quality of transmitted light through the glass. Flash lighting could not be used because the scanning process in the camera requires a source that is continuous and stable over the 16-second scan period. As the width of the individual stained glass panels is of manageable proportions (about 50 cm between the inner surfaces of the stone window mullions), it proved feasible to construct a uniformly illuminated panel based on a commercial photographic 'soft box', as shown in Figure 1.

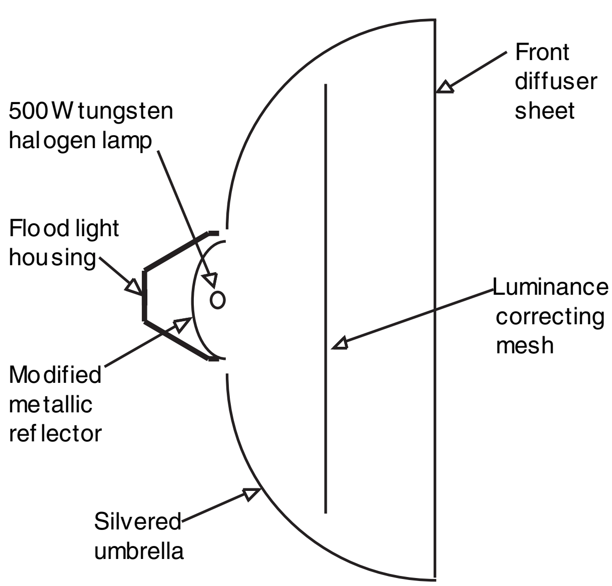

Figure 1. Schematic of 'soft box' constructed to back-light the windows.

A 500 Watt tungsten-halogen flood light was selected as the illumination source. The front glass of the lamp housing was removed, and the metallic reflector modified to move the lamp forward to the focal point of the parabolic curve of the silvered reflective umbrella of the soft box. The internal mesh sheet supplied with the soft box is designed to correct the distribution of light intensity so that a uniform luminance is achieved on the white diffusing sheet at the front. With careful adjustment, an average luminance level of 9200 cd/m^2 was achieved, with a luminance variation within ±10% across the usable front surface area of 50 by 60 cm. The colour temperature of the light is 3200 K.

The custom back-light was used for both the conventional photography (using tungsten-balanced film) and the digital photography. It was wedged in place between the stone mullions of the window and hand-held by an assistant standing on an external scaffold. Pieces of rubber foam were used to fill the gaps between the upper and lower front edges of the illuminating panel and the window glass, to prevent the 'leakage' of daylight, which would produce a blue cast at the edges of the image. The external protective copper window grilles were removed to prevent them casting shadows onto the glass, though it was not possible to remove the iron ferramenta which are cemented into the stonework and provide a matrix that supports the glass panels. The diffusion of light around the bars of the ferramenta softens, but does not eliminate, their shadows.

Stray light from two sources was found to be problematic: light originating from within the church, such as lamps and other windows, which produced unwanted reflective highlights on the glass surface; and daylight passing through the windows surrounding the illumination panel, entering the camera lens obliquely and causing flare. A second piece of apparatus was therefore constructed to eliminate both sources of stray light. This consisted of a truncated square pyramid about 1.5 m in length, with base dimension of about 60 cm, made of light-weight wooden dowels covered in black cotton material. This was positioned horizontally between the camera and the interior of the window on a separate stand, so that the front of the camera was shrouded by the open narrow end of the pyramid.

Scaffolding inside the church was used to support the camera tripod. Successive photographs were overlapped by about 30% of their height to ensure that there would be plenty of image area for registration during the mosaicing phase (see below).

Colorimetric Calibration

Colours in medieval stained glass were produced by mixing metal oxides with the molten glass during smelting: red was obtained from copper oxide, yellow from ferrous oxide, green from dioxide of copper, blue from cobalt, and purple from manganese. Since the red colorant was generally too dense, a thin layer was frequently flashed onto plain glass. All the fine detail in facial features, decorations, lettering, etc. was painted onto the coloured glass in a grey-brown enamel called *geet* or *arnement*, then baked onto the glass by re-firing in the kiln at moderate temperatures. This paint was a mixture of iron or copper oxide, ground glass, gum arabic and a binder such as water, wine, vinegar or even urine. A solution of silver nitrate could also be painted onto the glass to produce a yellow stain.[3]

In order to calibrate the colours of the digital images, a stained glass test panel of about 50 × 40 cm was specially constructed, containing 100 rectangular pieces of stained glass in a 10 × 10 array, leaded into a bronze frame. Each piece of glass is approximately 5 × 4 cm and is cut from stock made by hand using the same methods as in medieval times. The panel includes a full range of colours and densities typical of the medieval glass in the church windows, and is painted in several densities with several types of glass-paint. Colours of the glass patches were measured with a *Colortron* spectrophotometer from Light Source Inc., using the *Spotlight* attachment in transmissive mode. Absolute spectral transmittance was measured, with the unobstructed light source (tungsten) taken as the white reference. CIE L*a*b* co-ordinates of 20 representative pieces of stained glass are shown in Table 1. The density values are 'visual density' through the Status A filter set, and range from 0.09 for 'clear' glass up to 2.72 for deep red.

The glass test panel is being used as a transmissive colour calibration chart, in a manner similar to the use of an ANSI IT8.7/1 transparency target for a scanner. The panel is imaged by the digital camera using the same backlight illumination and imaging geometry as for the windows. A 3rd-order polynomial transformation is then determined by fitting the measured colour co-ordinates to the average red, green and blue (*RGB*) pixel values for each patch produced by the digital camera. From these an ICC input profile can be constructed and attached to the image files for subsequent processing and reproduction. Drift in the calibration, caused for example by backlight luminance changes over time, is checked by taking images of the panel before and after each set of images for a complete window, but this has been found not to be a problem.

Table 1. Colour and Density Readings of 20 Stained Glass Samples.

Code	**Colour**	**L***	a*	**b***	**C***$_{ab}$	**h**ab	**Density**
R1	Red	26.9	53.4	45.7	70.3	40.5	1.30
j3	Deep red	1.7	7.9	2.6	8.3	18.5	2.72
Y1	Pale yellow	90.8	-2.7	13.0	13.3	101.8	0.11
Y5	Yellow	73.0	10.7	69.4	70.2	81.1	0.34
Y7	Brown	41.4	32.5	67.8	75.2	64.4	0.91
G3	Green	57.85	54.9	7.2	55.4	172.4	0.59
G5	Yellow green	52.7	-14.3	47.0	49.1	106.9	0.68
a4	Grey green	64.3	-22.3	11.3	25.0	153.1	0.48
G7	Deep green	17.2	-42.3	1.6	42.3	177.8	1.63
B1	Light blue	53.3	-13.3	-45.9	47.8	253.8	0.67
B2	Mid blue	17.4	-20.7	-49.7	53.8	247.3	1.62
B3	Deep blue	9.6	-0.1	-51.8	51.8	269.8	1.96
B5	Grey blue	12.1	-11.9	-20.8	24.0	24.0	11.85
a0	Purple	33.3	8.5	-19.5	21.3	293.6	1.11
V1	Light violet	65.1	17.1	7.3	18.6	23.2	0.46
V4	Deep violet	38.0	23.1	10.5	25.4	24.5	0.99
j1	Clear	92.1	-2.6	13.9	14.1	100.7	0.09
d4	Light grey	84.8	-9.4	16.8	19.3	119.2	0.18
N1	Light mid grey	60.5	-6.7	-1.7	6.9	194.1	0.54
N2	Mid grey	51.1	-4.8	0.2	4.8	177.4	0.71

Constructing a Digital Image Archive

Each image frame from the digital camera is 3000 by 2320 pixels, corresponding to an area of glass 50 cm wide by 38.7 cm high at a surface resolution of 6 pixels/mm. This resolution is appropriate to the degree of detail in the window painting, as the finest brush strokes are about 0.3 mm. Each image frame on 6 × 7 cm film corresponds to an area of glass 50 cm wide by 58 cm high. Given that the film resolution is in excess of 100 lines per mm, the linear resolving power of the film is more than double that of the digital image. Each image on film could therefore be digitised to at least 6000 by 7000 pixels, if required. A Crosfield graphic arts desktop CCD scanner will be used to digitise all the transparency photographs at a resolution that equates to a standard 6 pixels/mm on the surface of the glass.

Each image frame from either source (film or digital) will be corrected for the spatial luminance profile of the backlight panel, using a smoothed polynomial surface function fitted to the measured luminance distribution. A single complete digital image of each window will then be constructed as a mosaic of the separate image frames by digital image processing, using an adapted version of software developed at the National Gallery in London,[4] ported onto a Hewlett Packard Unix workstation. This software determines the exact amount of overlap between adjacent image frames, then resamples them to produce a large seamless digital image. The size of the final image of one of the four-panel windows in the nave of the church (overall dimensions 3.55m high by 2.32m wide) will be approximately 20,000 by 12,500 pixels, requiring about 750 Mbyte of storage at 3 bytes per pixel.

The total area of stained glass in the 28 Fairford windows is about 185 m^2 (2,000 ft^2). The entire image capture process generated approximately 1,000 colour image frames of 21 Mbytes each, or 21 Gbytes of image data overall, requiring about 35 CD-ROMs for storage. For reproduction on the multimedia CD-ROM, image compression will be used to reduce the data volume down to about 300 Mbytes. This will be achieved by reducing the spatial resolution to 3 pixels/mm (giving a 4:1 compression), followed by a 16:1 JPEG image compression.

Physical Restoration Methods

Medieval artist-glaziers were extremely talented at choosing where to place the H-section lead strips, known as *cames*, which held the pieces of glass in place. Both the shapes of the pieces and the lines of the lead were an integral part of the artistic treatment. Unfortunately, as well as suffering the attention of iconoclasts and vandals, stained glass has usually been subject to external weathering by wind, rain, atmospheric pollution, and thermal expansion and contraction. Under such conditions over a prolonged period the glass inevitably fractures, and for centuries the only method of repair was to groze away a small amount of the original glass to make way for a 'repair lead', which served to hold the fragments in place. The addition of numerous repair leads over the centuries has eventually resulted in significant degradation of the visual integrity of the designs.

In the Victorian revival of stained-glass techniques, some glass restorers went as far as replacing individual heads of figures where the painted detail had been eroded away, such as in the work of Bolton at King's College Chapel, Cambridge.[5] In extreme cases, major sections of windows were replaced wholesale, a notorious example being the work of Chance in the upper half of the Great West Window at Fairford.[1] Often the medieval remains were simply discarded. Fortunately these replacement campaigns led to such a public outcry that they were stopped before too much medieval material was lost.

Contemporary stained glass restorers are extremely sensitive to the need to preserve the original material, and the importance of artistic integrity.[6] It is permissible to replace missing or irreparable fragments, provided there are clear indications of the original treatment, and that new work is clearly identified and dated. As an alternative to repair leads, it is now possible to mould a piece of thin plain glass to the surface profile of the original fragments, forming a 'glass sandwich', hermetically sealed to avoid fungal growth. Old repair leads can be removed and gaps from earlier grozing can be filled with a transparent filler such as epoxy resin or silicone rubber. In the process of restoration, radiography may reveal faint details which can be strengthened by painting onto the modern glass. This use of a physically separate layer, superimposed onto the original glass, allows the image detail to be restored from the viewpoint of the observer inside the church, whilst making minimal change to the original material.[7]

Restoration by Digital Imaging

Contemporary digital imaging techniques provide a non-invasive means of reviewing the state of a window prior to repair, and of visualising plans for its restoration. Because the appearance of stained glass changes with viewer position and lighting conditions,[8] scholars frequently work with photographic transparencies or prints taken by specialist stained glass photographers who chose the lighting conditions carefully.[2]

At King's College Chapel, Cambridge, the archive collection is held on 4 × 5" and 6 × 6 cm transparency photographs. An experimental image database was generated from these by scanning onto Kodak PhotoCD disks with the highest resolution available, i.e. the Base-64 option. Each image thus occupies 72 Mbyte of file space.

In a preliminary study into digital image restoration of the Kings glass, Tuddenham tried a combination of interactive and artificial intelligence techniques.[9] Repair leads were identified by the user through the graphic user interface. The computer then determined the extent of each lead by searching in the vicinity for neighbouring pixels dark enough to be treated as lead, i.e. with intensities below specific threshold values of red, green, and blue corresponding to lead. To avoid problems with shadows cast by the photographic lighting, representative points were chosen from the adjoining glass at a marginal distance away from the lead. The program then replaced areas identified as lead in the image with values determined by linear interpolation across the neighbouring areas, normal to the direction of the lead. This technique worked fairly well for smoothly varying regions such as robes, but proved to be totally inadequate in regions of significant detail, particularly in faces. Clearly it is unreasonable to expect computers to recover fine image detail unaided, unless more intelligence can be built into the restoration algorithms, for example by training on other similar image areas.

As an alternative we experimented with the image manipulation software Adobe *Photoshop* to remove repair leads by over-painting them with colour values matched to the neighbouring regions. The layer facility in *Photoshop* Version 3 allowed the over-painting to be constructed and manipulated separately from the main image, analogous to the physical glass layer restoration technique. A very useful facility proved to be the 'rubber-stamp' tool, which allows the image texture to be copied from a nearby region over the region of the repair lead, thus avoiding the creation of areas of colour that look artificial because they are too uniform. Figure 2 shows a small portion of the Great East Window at King's College Chapel, Cambridge, with the head of a Roman soldier attributed to the glazier-artist Vellert. The image on the left is the original; the image on the right is after creative retouching, an artist's impression of how it might have looked originally. In the hands of a skilled artist, digital image restoration promises to provide the best method yet of restoring the appearance of the original stained glass.

Figure 2. Restoration of painted detail on glass using Photo-shop. The original image is on the left.

Further Developments

A significant problem in the photography of stained glass, by either conventional or digital cameras, is the physical positioning of the camera in front of the glass, necessitating scaffold platforms and a great deal of manual labour. There is a real need for development of a remote-controlled robotic platform that would convey the camera to each position inside the window, and optionally an illuminating panel to the corresponding position outside the window. Initial studies at Kings College indicate that suitable structures are feasible.[10]

Scholarly activity in stained glass is facilitated by the Corpus Vitrearum Medii Aevi (CVMA), which has specified comprehensive standards for the recording of the state of stained glass, its history and interpretation. Accurate reproductions of the glass are always accompanied by restoration charts, which show the extent and date of repair work. Cothren showed that computer graphics could be applied to the preparation of such charts.[11] Techniques similar to those used for the digital analysis of watermarks[12] could be suitable.

It is now possible to generate such a restoration chart as a superimposed layer on the digital image, using the standard feature of *Photoshop*. It is also helpful to see a view of the stained glass from the outside, which can often provide additional clues in determining which are repair leads. The external image can be mirrored for direct registration on screen with the inside view.

There are extensive collections of photographic images of stained glass, in both monochrome and colour. Many of the colour collections have suffered fading, but since the process is well understood, the images could be restored to their pristine state, which would make it possible to compare up-to-date digital images with historic ones and so monitor changes in the glass itself.

While *Photoshop* has proved highly effective in treating images of stained glass, there is great scope for algorithmic methods. For example, an augmented version of the 'rubber-stamp' technique might analyse the region of the image under the source cursor to determine the parameters of colour, texture, orientation, etc. These parameters could then drive an image synthesis model that would create under the destination cursor the correct texture to simulate the glass painting.

Conclusions

We have developed new techniques and apparatus for photography of stained glass *in situ* and for constructing digital image archives of stained glass windows. Digital cameras hold great promise for image capture in future and their utilisation will be facilitated through the development of remote-controlled mobile supporting platforms. Tools such as *Photoshop* can produce excellent results in artistic restoration of the painted detail in stained glass, in the hands of a skilled user. Stained glass is a fascinating but under-explored medium, to which digital imaging can contribute significantly to a better understanding, for both scholars and the public at large.

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