

# PERIODIC PHOTOGRAMMETRIC MONITORING AND SURFACE RECONSTRUCTION OF A HISTORICAL WOOD PANEL PAINTING FOR RESTORATION PURPOSES

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## ABSTRACT

The Westminster Retable is a work of art occupying a central position in late thirteenth century painting in Europe. It is 3.4m long, 1m high and about 0.1m thick and consists of an oak support which carries numerous decorative and structural features and materials including: wood carvings, paintings, glass, dowels, metal, stone and vellum. During the restoration process it is necessary to conduct environmental response monitoring and mechanical deformation checking to ensure the integrity of the Retable. A multi-image digital photogrammetric system has been chosen for this purpose since it offers a periodic method of non-contact recording. However the image record and its associated spatial data can be used for other purposes including providing the basis of a visual database used to manage the conservation process and to automatically generate a 3D surface model which allows the art conservator to make measurements and comparisons between different parts of the structure.

This paper describes the use of a photogrammetric system for high precision monitoring during the conservation process using multi-photo network adjustments, camera calibration and stochastic deformation analysis techniques. The technique has been able to monitor discrete points on the surface of the Retable to precisions of 20 micrometers. Techniques are then described which have allowed the automatic generation of an accurate surface model from the multi-photo image record. This latter work draws upon an integration of point interest algorithms, multi-photo image matching, epipolar geometry, extracted lines and edges to automatically generate a dense point cloud and triangulated surface model. These methods are integrated within an error propagation model to ensure the precision and reliability of the extracted data. The model is currently being integrated into the art conservation database system with the aim of allowing conservators to make dimensional and shape comparisons between some 3000 different structural elements on the Retable.

## 1. INTRODUCTION

The Westminster Retable is the oldest surviving easel painting in Britain. It originally furnished the High Altar of the Abbey and was executed in Westminster during the second half of the thirteenth century. It was the product of pan-European collaboration – Henry III's accounts show payments to British painters as well as to painters from France and Spain, some of the techniques employed in the painting are Italian, and materials for it were imported from as far as Afghanistan.

The core of the work was formed by six oak planks, which were joined by thirty-one iron dowels. Some of the front surface was carved to a depth of a few centimetres and the rest of the front was embellished with over one hundred smaller carved pieces of wood, attached with nails and wooden dowels. Joints in the wooden superstructure were sealed with parchment, and the entire surface was decorated. The reverse and all the edges were painted to look like porphyry, even though the Retable was embedded in a stone screen so the reverse and edges were never seen. The front was covered with gold leaf, painted scenes, stained glass, gems, enamels and cameos. The surviving painted scenes include three identifiable miracles from the life of Christ, together with figures of St Peter, St John the Evangelist, Mary and Christ.

The Retable is in a very fragmentary condition and more than half the gold leaf, painted scenes, stained glass, gems, enamels and cameos are broken or completely missing. Some of the losses are due to the efforts of souvenir-hunters but other damages and losses are due to the inherent properties of



Figure 1: Detail from the front surface of the Retable – prior to conservation



Figure 2: Front and rear surfaces of the Retable – prior to conservation

materials from which the Retable was constructed. The wooden structure changes dimension anisotropically with fluctuations in relative humidity. Daily and annual cycles set up tensions within the Retable that are complicated by the cross-grain joints and attachments. These tensions are eventually released by permanent changes in the wooden structure, which in turn cause fractures in associated brittle components, such as stained glass and paint layers. In addition to relatively large-scale movements (in the order of 1mm) that cause catastrophic failure and loss, small-scale movements (of less than 1 $\mu$ m) can cause air-gaps in laminates that significantly alter the optical properties of the composite structures. Many components have therefore broken and, of those that remain mechanically intact, some have been visually distorted.

The physical condition of the Retable prompted concern and tests in the 1970s and 1980s lead to the establishment of a major restoration project, of which photogrammetry is an integral part. This paper describes a new method of documenting the process of restoration which is based on a spatial database founded on a common 3D coordinate system which can be used both for referencing and monitoring purposes.

## 2. PHOTOGRAMMETRIC MONITORING

The (on-going) restoration project is addressing the immediate physical needs of the Retable – removing accumulated layers of dirt, a layer of paint that was applied in the eighteenth century, thinning a seven-hundred-year-old discoloured varnish and securing delaminated paint and glass. In addition, the project is addressing the environmental conditions in which the Retable will be displayed, when returned to the Abbey. For both these aspects of the project, a dynamic and accurate 3D assessment of the Retable was required. Monitoring change in dimensions with environmental change was necessary in order to establish safe limits for the control of relative humidity. It was also required in order to assess the response of the Retable to physical movement. Some of the conservation operations could be carried out with the Retable in its normal vertical position,

but other operations were easier to execute with the Retable in a horizontal position – the conservators needed to know whether it would be safe to lay the Retable down for long periods of time.

Monitoring was to be carried out on a periodic basis with an initial epoch to determine a starting size and shape followed by interim epochs taken at selected times during the restoration process. The precision of well-defined features was to be within 0.2mm, with no monitored feature location to be worse than 1.0mm. Such levels of tolerance for periodically measuring a 3 metre-long object over several years could not be achieved using conventional techniques. A non-contact method of measurement was required because of the physical fragility of the surface of the Retable.



Figure 3: The Retable in its vertical supporting structure  
2.1 Data processing

Photogrammetric monitoring is primarily dependant on ability to locate homologous imaged “features” to sub-pixel accuracy and the dimensional stability of the digital camera and subject during imaging. Monitoring requirements are well within the precision attainable from multi-photo digital photogrammetric

monitoring (Fraser 2001) provided retro-reflective targets are used. In this case, following tests on glue permanence, it was possible to use standard engineering grade retro-reflective targets 2mm in diameter in areas of bare wood and to use “natural points”, with an acceptance that the precision of these would be lower, in painted regions.

A multi-photo network design could then be instigated based upon the constraints of the conservation studio, the requirement to monitor both sizes of the Retable and the imaging properties of a Kodak DCS460 camera fitted with 28 and 24mm lenses. The chosen network design is shown in figure 4. The datum for the coordinate system was defined by selection of key retro-targeted points on the structure, with scale defined by calibrated invar metrology scale bars. A self calibrating bundle adjustment was used to ensure rigorous data processing.

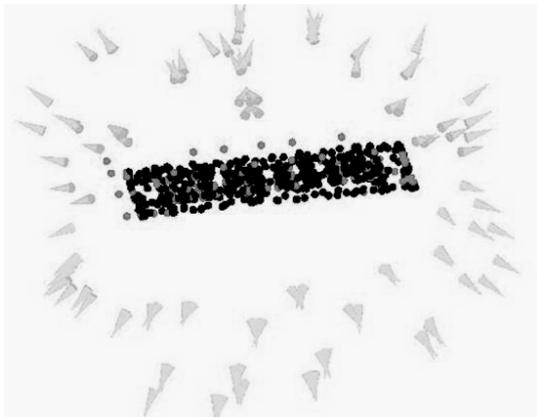


Figure 4: Photogrammetric network – black points are natural features, red points are retro-targets.

Number of target image observations	14,275
Number of exposures in the network	108
Number of targets and natural features	483
RMS image residual	0.84 $\mu$ m
Mean precision of target coordinates	20 $\mu$ m
Worst case target precision	90 $\mu$ m
Relative precision for the network	1 : 202,000

Table 1: Typical adjustment data

The series of bundle adjustment outputs consisting of the XYZ coordinates of targets and natural features, the exterior orientation of each photo in the network, the interior orientation (calibration) of each camera in the network and their associated variance / covariance are described with respect to the coordinate system datum. This data must be processed to determine which (if any) points have moved significantly and then to present any movement in an appropriate manner to the art conservator. A valid test of movement requires that the datum of the object coordinate system must be based only on 3D points which have not moved. The method chosen utilises the differences between object co-ordinates at each epoch in conjunction with their associated covariance matrices. Full details are given in (Robson 1995), but in essence the method proceeds according to the following steps:

- An initial common datum is provided by the method of inner constraints including all target coordinates in the constraint matrix.
- A global congruency test is carried out to determine if there is significant movement between the two epochs
- Any unstable points are removed one by one. Each time a point is removed the datum will change and is

redefined by a localisation procedure which transforms both the targets and their associated covariance matrices to the new datum

- A local congruency test is applied after the removal of each point

## 2.2 Results

Monitoring whilst upright indicated that the Retable warped, to the order of +/-1.5mm, but did not twist. Dimensional changes in the plane of the Retable were found to range between -0.9 and 0.7mm. Most movement was found to occur in the end panels which were less mechanically constrained (Figure 5). Significantly there were no identifiable disparate movements between points located either side of joins in the horizontal supporting boards.



Figure 5: Epochs 3 to 4 (Retable in upright position in supporting cradle).

A horizontal support could therefore be constructed that would accommodate the degree of deformation that the Retable would encounter due to change in orientation and changes in humidity. The support distributed tensions so that new cracks should not nucleate and existing cracks should not significantly propagate. Comparison of several photographic surveys of the Retable, undertaken during its treatment, indicated that no visible damage has been caused by its change of orientation.

Figure 6 demonstrates changes occurring in laying the Retable on its rear surface. After 1 week, settling of the order of 1.6mm has occurred in the centre whilst the outside edges have lifted by up to 1.4mm. In this case the level of detectable movement was 0.13mm

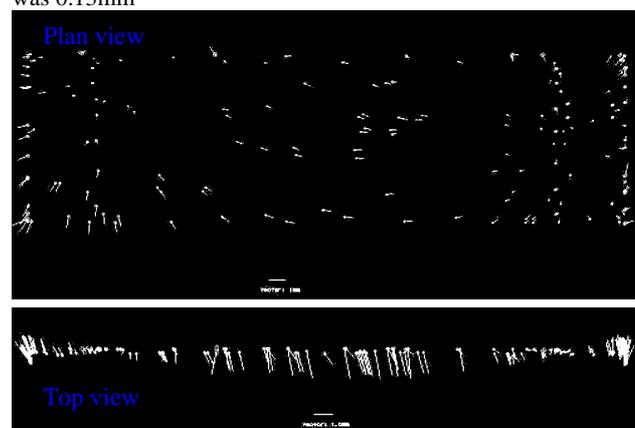


Figure 6: Deformation between Epochs 4 and 5 (Retable rotated into a horizontal plane)

## 2.3 Photogrammetric monitoring summary

Multi-photo photogrammetric monitoring has proven a useful tool in the periodic monitoring of the Retable giving the

conservator confidence that no damage is occurring due to environmental change.

Having established a correlation between humidity levels and degrees of deformation, the conservators were able to specify the level of environmental control that is necessary to ensure the long-term stability of the Retable. When the conservation treatment is complete, the Retable will be housed in a glass display case in Westminster Abbey which should provide an environment that would preclude the need for further intervention for between fifty and one hundred years.

### 3. SURFACE MEASUREMENT

Whilst it would have been possible to use laser scanning technology to provide a 3D surface suited to the requirements of the spatial database, close range photogrammetry was selected to provide a 3D surface model as it avoided the necessity of shining a laser onto the panel surface. In order to achieve dense measurements of discontinuous and sharply varying surfaces a multi-station convergent photogrammetric reconstruction method has been developed (Papadaki 2001). The method integrates target measurements and image processing algorithms within a convergent multi-station digital photogrammetric framework. The method can produce a dense cloud of accurate object surface points provided there is sufficient surface and image texture. Furthermore it has the advantage over laser scanning in that it can directly incorporate the automatically extracted 3D edge information necessary to achieve an accurate model of the complex surface of the Retable.

The methodology involves the iterative densification of a sparse 3D triangle network using the 3D locations of natural features, such as points and edges, which are detected and measured in multiple images. The iterative triangle model provides both a surface model and a geometric constraint for the reconstruction process making the system capable of processing complex shapes and able to account for occlusions. The resultant model can be used within the spatial database to drape imagery onto the 3D model in order to produce a realistic and measurable representation for the art conservator.

#### 3.1 Surface generation method

Our approach to model densification deals with the problem of image point correspondence in a multiple image network. The network set-up is implemented in a digital Close Range Photogrammetry System (Vision Metrology System VMS (software), Robson, Shortis), where the retro-reflective targets, which form the basis of the initial sparse triangulation, have been measured and the imaging geometry already recovered for the purposes of deformation monitoring. Standard photogrammetric bundle adjustment procedures provide the information necessary to ensure calibrated image geometry and agreement to a specified datum definition.

The process of densification is initialised by applying an interest operator, (Forstner 1987), to create a seed point cloud. A

multiple image point correspondence can be reliably established for a number of these seed points by defining criteria selected from a combination of radiometric and geometric properties.

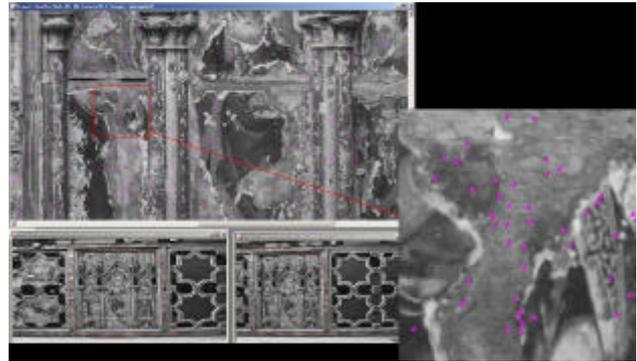


Figure 7: Interest points computed during second iteration  
Precise correspondence is subsequently achieved with a least squares based image patch matching routine (Gruen 1988) that has been modified to use information derived from comparing corresponding image and object triangle shapes. The number of conjugate points is increased in a series of stages, in which the matching routine is applied to all images in the network. The conjugate point search is optimised through the use of epipolar geometry constrained by common 3D bounding triangles and their projection into each image. This process generates a conjugate point list, which is filtered through photogrammetric intersection to produce points with three-dimensional coordinates at a specified level of precision. The results are imported into a bundle adjustment process to provide a rigorous evaluation of the network.

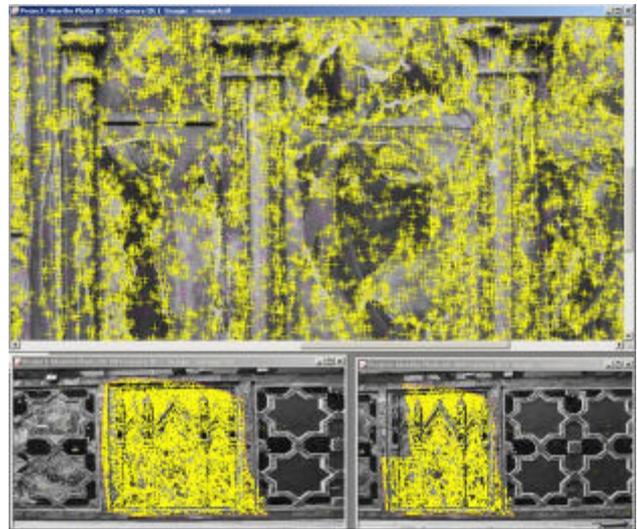


Figure 8: Some 25,000 matching points after 2<sup>nd</sup> iteration

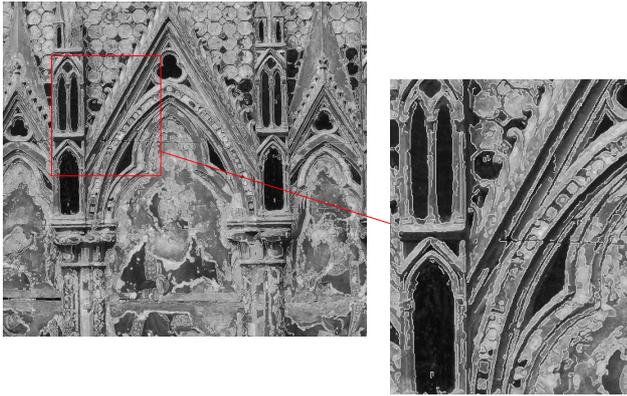


Figure 9: Inclusion of edge information

The final 3D point cloud prompts the update of the Delaunay triangles. Upon examining the updated 3D surface model, potential model fidelity discrepancies due to discontinuities and gradient changes can be successfully addressed by introducing edges. The single pixel width edges in this example have been extracted using a canny edge detector and converted into a linked list of edge points so that they can be processed in a similar manner to the initial interest points. To achieve this edge detection is initialised in a seed image and the subsequent process of creating 3D edge segments proceeds in the manner described for the interest points. Once computed in 3D, the points are grouped to produce 3D edge segments which may then be used to constrain the existing triangulated surface. This method provides a high level of model fidelity.

#### 3.1.1 Summary of the multi-photo surface extraction method

- A multi-photo convergent image set are used to automatically measure the Retable surface and generate a surface model
- Network adjustment ensures correct image geometry
- A generate basic triangulated surface model from target point data is produced (such a model is consistent in both image and object space)
- Seed interest points are identified (Foerster operator) on a triangle by triangle basis
- Multi-photo epipolar constraints are used in conjunction with triangle boundary information to identify search regions for possible homologues in other images
- Multi-photo patch matching with geometric constraints ensure accurate homologous point correspondence
- An intersection solution at a specified tolerance level validate the data and produce 3D coordinates
- Surface triangles are automatically updated at each iteration

#### 3.2 Surface measurement summary

The described approach to surface densification provides a dense surface point cloud with sub-millimetre level precision. This level of precision is supported with results of the network adjustment and has been validated against known engineering surfaces in the laboratory (Papadaki 2002). Quality of the derived model data is further supported by the fidelity of the model when inspected in 3D with the calibration corrected imagery draped onto the triangle network.

The technique can resolve issues such as occlusion by integrating measurements from different views. Fine detail can be successfully included by careful selection of minimum image

processing patch sizes and careful image acquisition at an appropriate magnification. Spurious data, due in the case of the Retable, to repetitive decorative patterns are filtered out by the geometric and radiometric constraints employed throughout the process.

Ultimately, the method is limited by the image network geometry and the existence of and appropriate surface views and texture content within the images. In this case, the use of edge detection has provided significant advantages over other methods due to the nature of the surface of the Retable, which is characterised by sharp gradient changes and linear features produced by paint layering and wood frame designs.



Figure 10: Rendered surface model of the Retable

#### 4. THE ART CONSERVATION DATABASE

Photogrammetric surveys were undertaken primarily to assess the mechanical response of a complex object to its environment. However, as a result of these surveys, a 3D model of the Retable was created that offered other functionalities. These additional functions – static measurements and spatial referencing – are a consequence of the existence of a dimensionally accurate digital image.

A spatially referenced image of the Retable enabled the creation of a database that facilitated the documentation of the conservators work. Traditionally, a conservator will generate a written record of their work as it progresses. This is document is supplemented by the results of technical analysis and visual records such as X-rays, Infra Red reflectographs, and photographic images of the object before, during and after treatment. If the object and the treatment are relatively straightforward, involving relatively few conservators working over a period of months, then such methods of documentation are completely appropriate. However, the complexity of the Retable and its treatment required project management support software that did not exist. Using principles related to those employed in GIS software, a conservation database was built.

A hierarchical description of the Retable was created as a framework for the five thousand or so separate components of which it is comprised. This included all original components (from the six oak planks to several hundred small gems) and all later additions (the wooden reinforcements attached to the back at the turn of the nineteenth century, etc). The boundary of each individual component was also outlined on the digital image (or multiple images – one for the front, one for the reverse, one X-ray mosaic, etc).

The conservators could then approach the Retable as an assembly of individual spatially related components. Access was either via a standard directory-structure type hierarchy or

via an image. The image would allow the automatic identification of individual components within a defined 2D area ( $x$  and  $y$ , using a click-and-drag box). Alternatively, the image would allow the automatic identification of individual components that were related in the  $z$  dimension (those including a specific  $x,y$  coordinate identified with a single mouse click). Individual components could be identified by the conservator on one image (say, that of the X-ray or reverse) and that component's location could be viewed (suitably transformed) on another image (say, that of the front).

The hierarchy and the image both allow access to the database, which consists of a series of records. The "identity" record holds administrative details of the object (title of the work of art, the name of the painter, etc). The "photography" record holds details of all photographs taken (location of area photographed, stage of treatment documented, etc). In addition to these global records, each individual component has a number of records associated with it, which can be updated by the conservator. The "structure" record holds data about the original composition of a component (from the length, breadth and thickness of an oak plank, to the colour and cut of a gem, etc). The "condition" record holds data about the current condition of a component (from 'intact exemplar' to 'deliberately removed', etc). The "examination" record holds the results of scientific examination of a component (from the dendrochronological details of an oak plank to the chemical composition of a gem, etc). The "treatment" record holds data about the sequence of a conservator's interventions (from the dates of treatments to the chemicals used, etc).

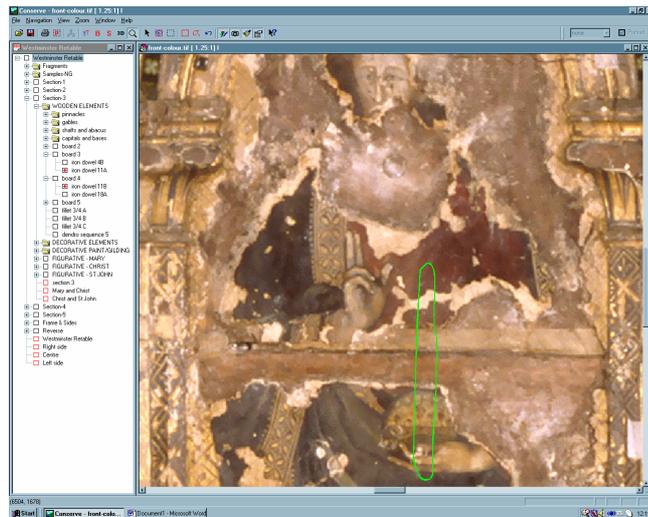


Figure 11: Position of a hidden iron dowel with respect to the painted image of Christ

All records can be searched by using the attributes with which the hierarchy was constructed or by selecting keywords that occur in the free text entered by conservators in their records. The results of a search are presented as a list of the relevant components, opening of the hierarchical structure in appropriate places and highlighting the component's outlined boundaries in the digital image. This allows all the conservators (there are half a dozen or so people with different expertise working on different areas at different times) to know who did what where and when.

In addition to this invaluable project management function, the spatially referenced digital image also allows accurate measurements to be made without direct physical contact with the Retable itself. Accurate measurements are to be made for art historical purposes to throw light upon the construction of this

thirteenth century product of international collaboration. Units of measurement were not standardised, so was the Retable the product of an English foot or a French foot, or possibly even a Spanish or Italian unit of measurement? Also, irrational ratios were commonly used in architectural constructions, so was the design of the Retable based upon a proportion such as the square root of two? Remote measurement with the 3D model will allow us to answer such questions without risking further damage to this historically important object.

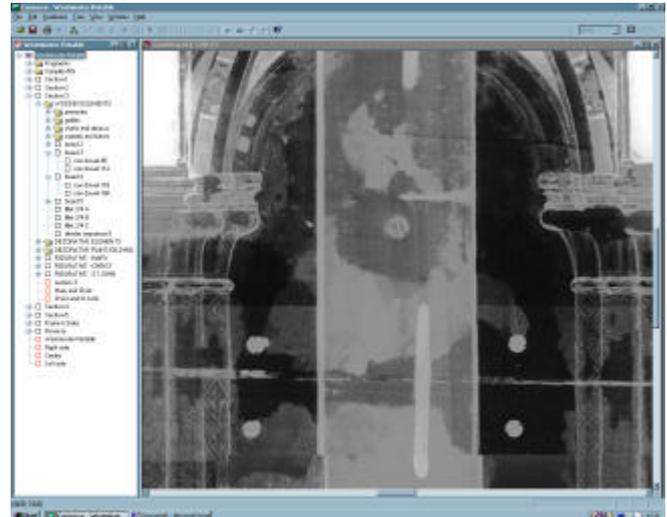


Figure 12: Position of the iron dowel (plus nineteenth century screws) as seen in X-ray mosaic

## 5. CONCLUSIONS

The use of photogrammetric monitoring and surface measuring tools within a purpose designed art conservation database has significantly contributed to the treatment of the Westminster Retable. The tools have also enhanced the conservator's understanding and documentation of this unique object and will assist in disseminating that understanding to a wider audience.

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## 7. ACKNOWLEDGEMENTS

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