3D VIRTUAL MODELLING OF A GOTHIC STAINED-GLASS PANEL

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ABSTRACT:
The paper illustrates laser scanning methodology applied to the study of a gothic stained-glass window: the work can help understanding how glass objects are measured by laser scanner, conforming to more parameters. A glass window from King's Chapel, Cambridge (UK) was modelled: a vertical *ensemble*, divided into more parts, made of glass, coloured during its realisation or coloured before being placed on the wall. Thus, a different sensitivity to laser beam is expected from glass. The acquisition was performed using Konica Minolta Vivid 910, with a 5 x 8 scan matrix. Registration via ICP algorithm was carried in 8 horizontal stripes. Scans seem to be quite homogeneous, except some lacunas, probably depending on a "brownout-effect" induced by the presence of stain structure, partly obscuring glass surface. Otherwise they could be depending on local condition of glass, causing loose of signal from the surface. Some details show a particular noise in the acquisition, probably caused by an outdoor metal scaffolding, especially in more transparent areas. A comparison with the acquisition of an object protected by a glass showcase is illustrated too, to study the response of glass material. It was argued that glass painted with non covering colours is more sensitive to such object while covering colours (or coloured glass) "stop" laser beam and give no noise. Besides with painted sheets, a 3D laser scanning model can give a sub-millimetrical mapping with the thickness of colour layers: thus, noise induced by the metal scaffolding can be evaluated too.

1. INTRODUCTION

The work is about 3D mapping of a glass surface and it shows how this material reacts to laser beam of measuring instrument, with specific reference to treated material. A complex surface was measured: a Gothic stained-glass window, from King's Chapel, Cambridge (UK), was scanned with a triangulation laser scanner instrument, Konica Minolta Vivid 910.
The application of laser scanning methodology to the survey of glass materials has already been performed within different fields, from cultural heritage to mechanical engineering and metrology (Columbia University Robotic Group, 2001; Ioannides et al., 2002; Nagai et al., 2004, ter Haar et al., 2005). In case of glass windows, a long-range laser scanner is generally used in order to virtually reconstruct the entire architecture. Thus, the aim is concentrated on the reproduction of the whole structure and this doesn't allow the observation on a high-scale of local phenomena due to laser beam/surface interaction.
Besides, within the field of smaller range virtual reconstructions, it is noticed that laser beam can penetrate the glass when this is transparent or colour-less, showing how superficial treatment and conditions of glass play an important role in the quality of acquisition.

2. HISTORICAL REVIEW

King's Chapel [Figure 1] is a magnificent Gothic building in King's College, Cambridge University, whose first stone was laid in 1446 by Henry VI and took one hundred years to be entirely built. Despite its apparent unity of style, the Chapel is a product of three separate periods of edification. Its importance in British history is determined by the fact that it is the last great monument of the Old Faith in England, before the 1534 Anglican schism. It is wholly decorated with coloured glass windows, made by some of the most important British painters and glass cutters of that time (Leader, 1988). A part of a glass window from Southern chapel was chosen from the building and measured.

Figure 1. King's Chapel, in King's College, Cambridge (UK), and the huge stained-glass windows decorating Northern side

3. MATERIALS AND METHODS

3.1 The glass surface

A glass panel from southern chapel was chosen, mainly made of two parts: the lower, with a central part exampling the Nativity, and four animals around it [Figure 2].

The central panel is made of two parts, but probably it was a unique one which broke during its pose and was fixed with stain (see diagonal stain adjustment) and is inserted in the lower register of the window together with rhomboidal panels.

Central square panel is painted; it was probably coloured before or during its placement in the wall with the other glass sheets. Its colours are all very light, from white (painted all over the panel, as a uniform background), to gold (for some relevant details), to red to define contours.

Figure 2. The lower and the higher register in the stained-glass window, exampling Bible scenes

The higher register has a different and more complex stain/glass structure: it is made of smaller and irregularly-shaped glass pieces [Figure 2]. It examples a Bible scene too, but instead of the former register it uses coloured (and not painted) glass, i.e. a glass which has been coloured during it production process through particular mineral compounds, such as blue for the dress of the character on the left or red glass for his hat. Thus, different details with different colours correspond to different pieces of glass fixed with stain. The same detail with one and only color, just like Bordeaux of the dress of the character on the right, is anyway divided into more pieces, and then fixed, but this can be both an aesthetic *escamoutage* and a solution to recover broken glass pieces of a sheet, perhaps.

In some parts, in this same register, additional colours were used subsequently to enhance contours or small particulars, such as the beards of the characters or the inscriptions on the boards (right inferior angle).

3.2 Instrumentation

The instrument which was used is a middle-range triangulation laser scanner with a red class 2 laser beam (i.e. emitting visible light, not dangerous but tiresome for eyes). Coordinates of each scanned point are calculated with reference to the coordinate system of the scanner, which is a three-dimensional right-handed Cartesian system, with its origin coincident to the point where the laser beam starts from the galvanometric mirror inside the instrument. A peculiarity of Konica Minolta Vivid 910 is that through its Charge Coupled Device CCD (resolution 640 x 480 pixels) RGB images can be acquired too and require no texturization processes as they are automatically referred to acquired meshes [Table 1].

Scan Range	0.6 to 2.5 m
Laser Scan Method	Galvanometer-driven rotating mirror
X Direction Input Range	TELE 111 to 463 mm MIDDLE 198 to 823 mm WIDE 359 to 1495 mm
Y Direction Input Range	TELE 83 to 347 mm MIDDLE 148 to 618 mm WIDE 269 to 897 mm
Z Direction Input Range	TELE 40 to 500 mm MIDDLE 70 to 800 mm WIDE 110 to 750 mm
Accuracy (X,Y,Z)	±0.10 mm (Using TELE @ distance of 0.6 m, Field Calibration System, Konica Minolta's standard, at 20°C)
Light Condition	Office environment, 500 lx or less
Output Format	3D data Konica Minolta format, STL,DXF, OBJ, ASCII points, VRML
Operating T / humidity range	10°C to 40°C, relative humidity 65% or less with no condensation

Table 1. Technical specifications of Konica Minolta Vivid 910 triangulation laser scanner used in the present research

The acquisition of the glass window was performed with Konica Minolta Vivid 910 laser scanner, with a distance between the instrument and the object of 0.7 m circa, using a Telescopic lens with a focal length f = 25 mm. The Charge Coupled Device CCD resolution of the laser scanner guarantees a maximum of 311040 points per scan. Under these conditions, the maximum size of scanned area is about 130 mm x 96 mm, while geometrical resolution of the acquired mesh, i.e. the

minimum expected distance between two adjacent points, is 0.2 mm x 0.2 mm (X and Y direction). The glass surface was measured with a 5 x 8 scan matrix, which means 5 scans along the horizontal direction and 8 on the vertical one; they were numbered from 1 to 5 across, right to left, and from A to H down, bottom to top. The first 4 stripes were acquired at a height of 0.7 m circa while the others at 1.3 m circa.

3.3 Post-processing of data

The acquired meshes were registered via Iterative Closest Point ICP algorithm in Polygon Editing Tool software (by Konica Minolta), keeping the central scan of each stripe fixed and aligning the adjacent ones to it, following a "lateral-growth" scheme (which is to say scans 2 and 4 are aligned to 3, 1 to 2, 5 to 4) in order to minimize the registration errors distribution. Thus the 5 scans of each stripe were merged into one.

The stripes were registered together [Figure 3] between couples and then merged all together to produce a single complete model of the stained glss window. The alignment errors are about 0.15 – 0.2 mm.
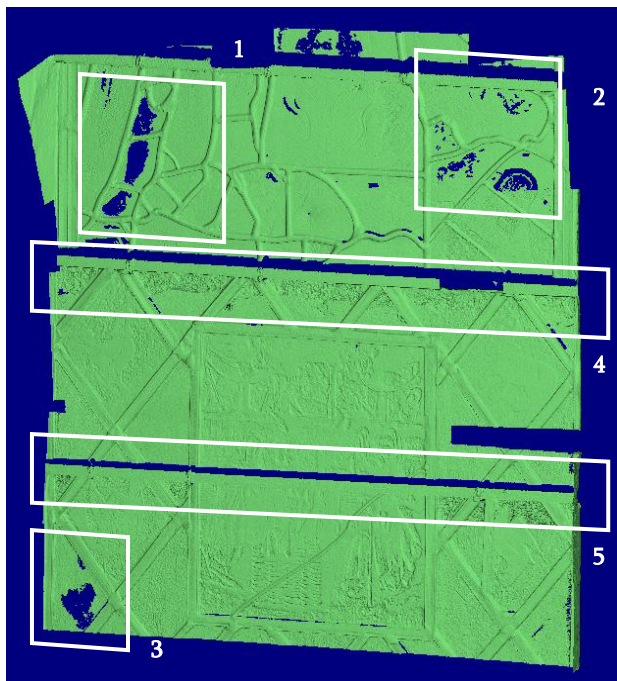

Figure 3. The global model of the stained-glass window with shading-mode visualization of the mesh and some relevant details (1 to 5)

Scanned meshes have an average geometrical resolution of 0.2 mm x 0.2 mm circa, as it was expected. Let us to consider a single scan, for instance T2F1: it was acquired with Telescopic lens (T), at higher height (2), in the 6th stripe (F), the 1st from right (1); it has an acquisition area of about 175 mm x 130 mm, while points are about 300,000, as it was expected. In fact, the presence of a stain structure slightly protruding may have caused a brownout of glass and that is why there is a smaller amount of points. Moreover, it is normal to "miss" a very small part of back signal from the surface when it is so reflecting.

As it can be noticed in the final model, where a unique mesh has all aligned scans, acquisitions are homogeneous and have no apparent deformations. This is an important result for this work: glass is a very special material, because of its high superficial reflectance and its complex micro-morphology

inside, making it react so differently to external solicitations. Thus the answer of this surface to the laser scanner beam is difficultly predictable.

Furthermore, some lacunas are noticed and mainly originated by brownout effect, earlier described. Other gaps may be caused by other phenomena, such as a particular combination of scanning angle and local macroscopic condition of the glass causing a loose of back signal.

If we consider details 1 and 2 [Figure 4], for instance, they have been acquired almost with the same scanning angle (in fact they belong to the same horizontal stripe).
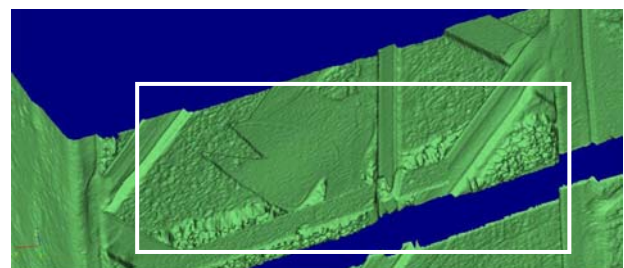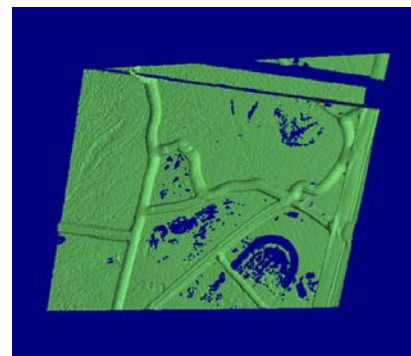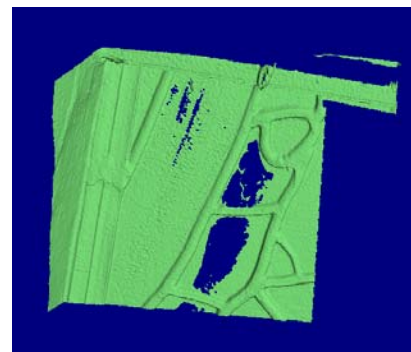

Figure 4. Details 1 and 2 from Fig. 3, showing lacunas, interpreted as a combination of more factors. Detail 5 showing its thickness with respect to the surrounding glass

Probably, scanning angle combined with local inclination of glass gave total reflection of the incident laser beam. Moreover, glass sheets are not perfectly coplanar one to another, and this is even more probable with small pieces. It could be a future development for the present research to calculate the accuracy the sheets were put together with, both one another and with respect to the wall.

Anyway, this explanation could be reinforced by considering that in all the three cases (details 1, 2, 3), the main colour producing such effect is white, the most reflective colour. The point is that white is the most used colour in the paintings of this glass window, but a part from these three details, white-colour lacunas where nowhere else noticed: probably these are

"hot spots", i.e. points with higher amount of white paint, enhancing the reflection phenomenon.
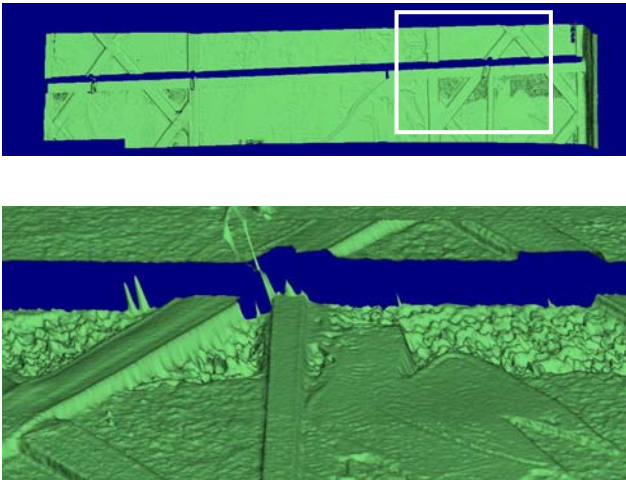

Figure 5. Zoom in of noise enhanced in a partial model of the window, probably caused by presence of a metal scaffolding behind the glass

Details 4 and 5 show a horizontal noise in the acquisition, which was interpreted as deriving by the presence of an outdoor metal scaffolding which caused absorption of the laser beam and induced a similar disturb, especially in transparent zones or zones with a non covering colour [Figure 5]. Noise is concentrated in those areas on the right of detail 5, which in fact was not painted with very covering colours.

The acquisition of glass painted with non covering colours seems to be more sensitive to the presence of metal objects while covering colours "stop" laser beam from crossing the glass. It was argued that even in areas decorated with glass coloured during its production there would be the same noise, because there wouldn't be the a covering colour layer to protect from absorption, but the acquisition revealed the opposite [Figure 6].

In fact, coloured glass is less sensitive to this same metal object behind, probably because of the different materials of which it is made of, i.e. the compounds used to colour it.

It was then argued that probably it is the refraction index which plays an important role in the sensitivity of glass and a comparison between this parameter and the results of the present research would be suggested.
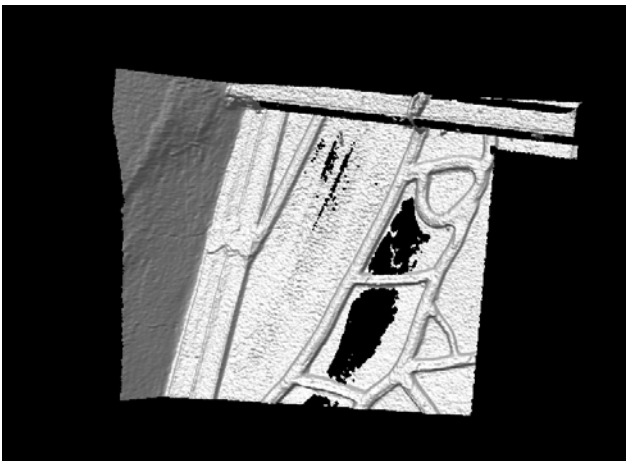

Figure 6. Shaded visualization of a mesh corresponding to a scan of a detail with coloured glass from higher register

3.4 Glass: a "barrier" or a "medium"?

In the present research, glass is the aim of the survey, but this material can be measured not only as a "barrier" to laser beam, which means as an independent object (like the stained-glass window in this work) but also as a medium before an object to be measured. In order to better understand phenomena related to glass acquisition, in King's Chapel, a wooden model of the fan-vault, stored in a glass showcase, was measured. In this case, glass is a medium, because the aim of the survey is placed behind it and laser beam has to cross glass before reaching the surface of the object and before the signal from the surface is received by the scanner. The involved glass is modern, completely transparent and colorless. The instrument was placed at 0.7 m circa from the glass or 1 m circa from the object. Wide lens (focal length 8 mm) was used in this application. Acquisition were performed orthogonally and not orthogonally too, from below and from above. At first, it was argued that glass would disturb and prevent from scan, being a thick filter for laser beam. Besides, resulting scans looked homogeneous and lacuna-free, leading to a uniform virtual reconstruction of the model of the fan-vault. Anyway glass introduced particular kinds of noise, with a hemi-circular shape, and spikes, interpreted as depending on a combination of factors like scanning angles and local features of glass, such as very small spots or particular micro-structural conditions.

In fact, these particular features were detected both with orthogonal and non orthogonal acquisitions, under different scanning angles.

In order to verify how these phenomena were depending on the presence of a medium between laser scanner and object, a sample (a stony tile) was measured in laboratory under natural conditions and behind a glass too, in an orthogonal position of the instrument, at 1 meter distance from the sample. For each of the three available lenses (Wide, f=8 mm; Middle, f=14 mm; Tele, f=25 mm), acquisitions were performed without and with the glass medium, which was a transparent colorless one. The acquisition of the object without glass aimed to give a comparison scan in order to better underline the "optical" and metric contribution of the glass medium in this experiment. The resulting scans looked homogeneous, non lacunose in both cases with each of the three lenses and spike-free. But when the object is measured behind glass, its corresponding mesh show a recognizable hemi-circular noise, very similar to the one detected in the model of the fan-vault in King's Chapel. Moreover, this phenomenon is more legible with higher focal lengths (Wide and Middle lenses) rather then Tele objective. It has been ascribed to the combination of more factors such as scanning angle and local condition of glass. Then, the two different acquisitions in laboratory, without and through glass, were registered one to another via ICP algorithm. The deviation between them emerged as a particular pattern of distribution of reciprocal distance and was interpreted as a deformation strictly depending on refraction phenomena induced by glass. In fact, it was argued that glass introduced a particular but recognizable error (valued around 1 mm), induced by the different refraction index air/glass and glass/air, causing a translation of signal from laser scanner to object and from its surface back to the instrument. Tele lens show the most defined deformation pattern and that is why it was chosen for non orthogonal acquisitions too, at the same distance of previous scans. The resulting meshes were very similar to the orthogonal ones:

without lacunas and spike-free, presenting the same deformation pattern, but with a different distribution on the sample.

Therefore the scanning angle plays an important role in the deformation of the acquired surface.

The entity of deformations depends not only on the refraction index of crossed medium (which makes glass more or less refractive than air and decides for the size of translation) but also on the thickness and color (influencing the refraction index) of the medium.

From the description of this experiment, the complexity of phenomena encountered when measuring glass is shown. Thus, a phenomenon like the absorption from the outdoor metal scaffolding is predictable. If we imagined that the aim of the survey was not the glass window but the metal scaffolding outdoor, the noise in the scans then would be considerable the result of the scan of the scaffolding through glass. The fact that the acquisition through glass is so "disturbed" [Figures 8-9], let us understand the impact that colored and painted glass has on laser beam crossing it.

3.5 Metrical evaluation of modelled stained-glass window

Acquisition of a stained-glass window with a sub-millimetrical sensitive instrument can provide interesting information on local micro relief of its decorative details [Figure 7]. In fact, particularly with painted sheets, it is possible to have a micro-mapping of the surface with indications on the thickness of each coloured layer.

Figure 7. Comparison between virtual mesh and photograph of the painted detail of the basket in the middle of central panel

The method here illustrated is about the use of particular planes fitting the surfaces under examination. A plane is identified with three or more points, placed not consequentially: fitting plane has minimum distance with all of them. The first reference plane is corresponding to the glass sheet (background paint-free plane), in regions without any painted colour, while the second plane is corresponding to the paint. An evaluation of average distance of the two planes provides information about thickness of the examined paint layer [Figure 8].
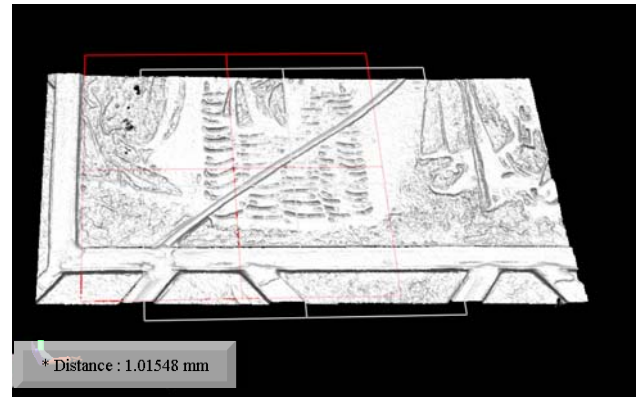

Figure 8. Height definition of a painted layer in the particular of the basket, lower register, 1.0 mm circa

The same approach can be used in the measuring of noise induced by the metal scaffolding. In a selected area of the disturb, more can be chosen as references to create a plane: the distance between it and a second plane, calculated from the stained structure, gives a metrical evaluation of metal-induced noise [Figure 9].
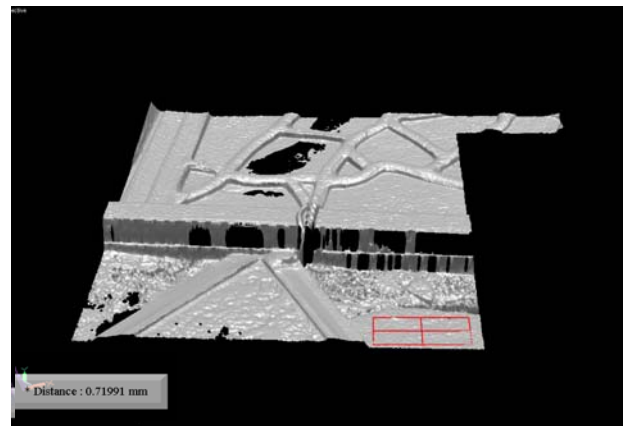

Figure 9. Evaluation of thickness of noise from metal object in the shaded mesh with respect to the surrounding glass

4. CONCLUSIONS

A 3D mapping of a gothic stained-glass window was performed: the application of laser scanning methodology with a mid-range instrument gave the opportunity to observe some local phenomena involved in the acquisition of this kind of object. In particular, coloured and painted glass sheets were considered: the comparison show that the variation of refraction index due to the different superficial treatment or features of glass material causes different reactions to the incident laser beam. This result is also confirmed by an experimentation

related to an object protected by a glass surface. Moreover, the 3D virtual reconstruction gave the chance for a metrical evaluation of paint layers on the glass surface and noise produced during the acquisition by the presence of a metal scaffolding.

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