Documentation and Analysis of a Medieval Tracing Floor Using Photogrammetry, Reflectance Transformation Imaging and Laser Scanning

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The fifteenth-century tracing floor at Wells cathedral is an extremely rare survival in European architecture. Located in the roof space above the north porch, this plaster floor was used as a drawing and design tool by medieval masons, the lines and arcs inscribed into its surface enabling them to explore their ideas on a 1:1 scale. Many of these marks are difficult to see with the naked eye and existing studies of its geometry are reliant on manual retracing of its lines. This paper showcases the potential of digital surveying and analytical tools, namely photogrammetry, reflectance transformation imaging (RTI) and laser scanning, to extend our knowledge of the tracing floor and its use in the cathedral. It begins by comparing the recording processes and outputs of all three techniques, followed by a description of the digital retracing of the tracing floor to highlight lines and arcs on the surface. Finally, it compares these with digital surveys of the architecture of the cathedral cloister.

Keywords: *digital heritage, photogrammetry, reflectance transformation imaging, laser scanning, medieval design*

INTRODUCTION

As a team of researchers at the University of Liverpool, we are investigating the design and construction of English medieval vaulted ceilings. A central aim of the project is to understand the design processes used by medieval masons, with one of our case study sites being Wells cathedral. Our main method to achieve this is to produce a laser scan survey of church and cathedral interiors. This 3D data is then processed in order to extract the underlying geometry of individual vault ribs, allowing us to reverse engineer their design process. However, in order to test our understanding of medieval design practices it is necessary to explore evidence besides the built vault fabric, and a prime asset for this is the surviving tracing floor at Wells.

The tracing floor is a level, 5.5 x 6.5m plaster surface located in the roof space above the north porch (figure 1). Here the masons inscribed lines and arcs into the plaster to investigate design ideas prior to construction. The tracing floor has previously been documented using analogue techniques, notably by Colchester and Harvey (1974) and Pacey (2007). However, digital surveying and analysis tools have the potential to uncover elements that are difficult to see by eye, which we explore in this paper. Once the digital survey process is completed, this also gives us an opportunity to compare the geometry found on the tracing floor with that used in the cathedral's vaults, in particular the apparent match with the cloister's east walk (figure 2) which was previously observed by Pacey (2007). Our research therefore takes a reverse approach to architectural design today, working not from digital designs to material fabric, but instead from material fabric to digital versions. In this way we can document and analyse existing works of architecture, in particular their design processes, using advanced digital methods.

Figure 1
Wells tracing floor, where inscribed lines can be seen on the surface.

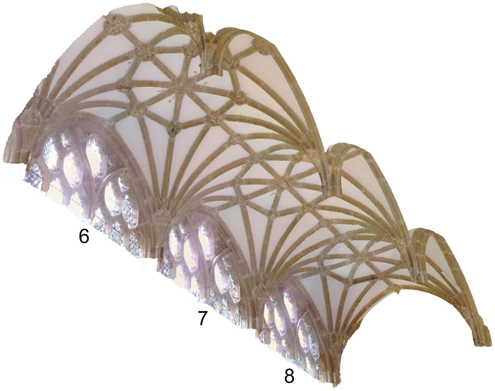

Figure 2
Mesh model of the east cloister vaults at Wells cathedral (bays 6-8, numbered N-S).

This paper will first document the three methods used to record the tracing floor: photogrammetry, reflectance transformation imaging (RTI), and laser scanning. Then it will discuss the respective strengths and weaknesses of each method based on their digital outputs. Next it will relate the process of digitally retracing the incised lines and arcs which these outputs have revealed on the tracing floor's surface. Lastly, it will briefly discuss the digital methods used to survey and analyse the vaults in the cathedral cloister, comparing our hypothesis for their 2D and 3D design processes to the geometry found on the tracing floor.

METHODOLOGY

Our survey of the tracing floor had to be precise in order for any comparison with the cathedral's fabric to be meaningful. Consequently, we decided to test three methods to ensure comparative accuracy. This also gave us the opportunity to compare each digital surveying method and their respective outputs. Protecting the floor itself was of the utmost importance and we strategized carefully to avoid damaging the plaster surface. Equipment was either hung from roof joists above or positioned on carpet tiles laid over the floor. The latter also acted as a useful surveying grid.

Photogrammetry

The first method which we used to record the tracing floor was photogrammetry, a process where hundreds of digital photographs were taken on site and composited together using Agisoft Metashape to create a full 3D digital model. We have previously undertaken detailed analysis of photogrammetry as a method to survey vaulted ceilings, finding the technique to be inadequate, as the distance between the camera and subject was too great to give a level of detail meaningful for analytical purposes. Consequently, we opted for laser scanning as our standard method (Webb et al. 2016). The tracing floor, by contrast, can be photographed at close range and photogrammetry therefore has much greater potential for capturing fine details. This can be seen in comparative projects such photogrammetric imaging of a large-scale Diego Rivera fresco mural, enabling an accurate record of it in 2D as well as fine 3D details such as the layering of paint (Schroer et al. 2018). The project, however, acknowledges the issues of data processing over 1500 photographs taken with a 50-megapixel high resolution camera. Similarly, Guidi et al. (2014) were able to survey at depths of around 1mm to capture inscriptions on a historic temple using photogrammetry, and acknowledged it was uncertain whether a laser scanned equivalent could achieve the same detail. Precedent therefore suggested photogrammetry as our first choice for the tracing floor survey. For our experiment, hundreds of digital photographs of the floor were taken systematically in four stages using a Sony A7 Mk3 camera:

- First stage: photographs taken at an oblique angle looking across the floor, with a 24mm focal length.
- Second stage: photographs taken with a wide angle looking straight down at the floor to record the wider context, with a 24mm focal length at a distance of 1.4m.
- Third stage: photographs taken from a narrow angle looking straight down to the floor to record detail, with a 50mm focal length at a distance of 1.2m.
- Fourth stage: photographs taken from a narrow angle with a slightly oblique view towards the floor's edges to record any missing detail, with a 50mm focal length at a distance of 1.2m.

The roof joists in the space containing the tracing floor are below head height, which made precise positioning of the camera difficult on some occasions (figure 1). On the other hand, they also provided useful supports for an opened tripod with the camera pointing downwards, as well as a linear sequence which we could follow to ensure all details were captured. The space has no artificial lighting and the only natural light enters from a single north-facing window. In daylight this provides good ambient light to the north of the tracing floor. However, the light gets gradually poorer the towards the south side of the floor (approximately 1/10 the brightness in the south compared to the north), requiring two flash guns to be used to balance the lighting conditions.

Once we were satisfied that we had enough photographs, these were composited together using Agisoft Metashape, which utilises perspective differences between images to evaluate the floor and the surrounding scene's geometry. A full 3D digital model was then produced in point cloud form, which was converted to a mesh model and orthorectified images as required. Whilst the 3D model did highlight some of the deeper scratches on the floor's surface, it was the orthorectified images that proved to be the most useful in identifying incised lines and arcs, provided that they were exported at a sufficiently high resolution: 0.25mm per pixel giving a total image size of over 500 megapixels. Though we experimented with using the mesh model, we found that tracing the orthomosaics using conventional drafting software was faster, more accurate and yielded more satisfactory results. The orthomosaics were not without problems though, the main issue being variable image quality across the surface, namely pixilation and changing lighting conditions. This meant that it was impossible to come up with a uniform way of identifying lines and arcs, which had to be performed on a case by case basis.

Whilst the photogrammetric survey enabled us to view the floor orthographically, it did not necessarily offer anything new compared to previous surveys completed with analogue techniques. The main difference between these analogue methods and our photogrammetric survey is the potential for human error: the digital tracing floor orthomosaics are much less likely to include mistakes in the recording process, as they are based on orthorectified photography, removing distortions potentially apparent in the previous analogue survey. Additionally, detailed recording could be made at a computer screen, rather than in-situ in the roof space of a cathedral, which has limitations. However, ideally one would do both, enabling checking against reality during the identification and recording process. Very fine lines, sometimes under 0.25mm wide/deep, were also difficult to record accurately (but less problematic for wider and/or deeper marks), and it generally was not possible to establish line depth. Nevertheless, the photogrammetry orthomosaics will provide an accurate digital record for researchers to use in the future (figure 3).

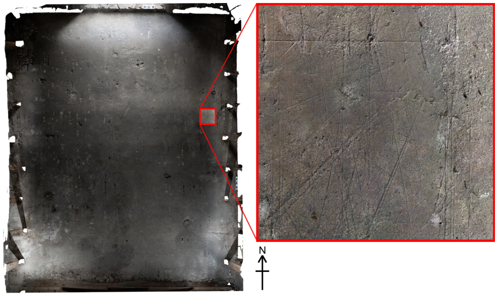

Figure 3
Orthomosaic of the tracing floor created using photogrammetry.

Reflectance transformation imaging

The second method we investigated to help uncover the secrets of the tracing floor was RTI photography, which has the potential to reveal details that are difficult to see by eye or with photogrammetry. This involved taking multiple images from a static location, but lit from different angles. The results were processed in software to create a synthetically relightable image where users can light a target area from any direction. This can simulate the effects of raking light, bringing out very fine marks and surface textures, and has previously been used mainly in the field of archaeology (Mytum et al. 2019).

Photographs were taken again using a Sony A7 Mk3 camera, rigidly mounted in a static position looking directly downwards at a target area of the tracing floor (approximately 400x300mm). Each image needs included a scale bar and two reflective spheres, similar to but larger than metal ball bearings. The distance of the target area was measured corner-to-corner, in this case approximately 500mm, then multiplied by four (approximately 2000mm) giving the ideal distance from the target to the light source: a hand held flash gun. Maintaining a consistent distance is essential to avoid variation within an image set, this is done using a piece of string of the right length. Placing the flash gun at this distance reduces the effects of parallax in the lighting whilst still ensuring it is close enough for the flash to be effective. For some image sets the distance had to be reduced to 1500mm due to obstacles. Next, the flash brightness was tested for correct exposure and the flash power adjusted as necessary. The camera was set to a low ISO with a moderate aperture (f8) and a fast shutter speed (1/200). Once this setup was completed, a set of photographs were taken as the flash gun was repositioned across a 2000mm hemisphere over the target. Photographs were taken with the flash positioned every 45 degrees in plan (8 groups of images) and every 15 degrees vertically (5 images per group), with some intermediary images giving around 60 photographs in total which record the exact same target area lit from different angles by a stable light source (figure 4).

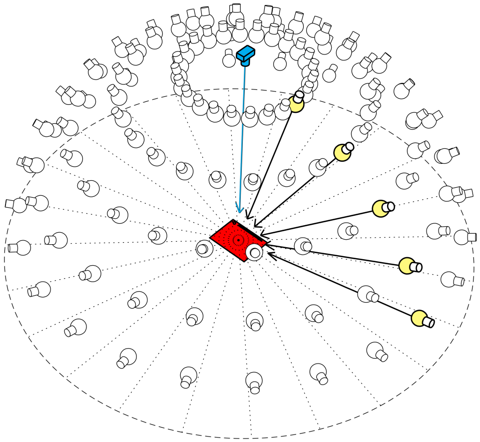

Figure 4
Example diagram of hemisphere setup, showing the target area (red), camera (blue) and light sources, showing a vertical run (yellow).

The process of surveying the tracing floor using RTI was relatively straightforward, the main exception being working on a target area close to the edge where the pitched roof and its supports made some photographs difficult to capture. The other issue was only being able to capture an area of approximately 400x300mm due to the camera resolution and flash distance requirements described above. The recording of each target area took around 25 minutes and we only had limited access to the floor because of guest tours operated by the cathedral, for which the tracing floor is a central attraction. Therefore, we were only able to record part of the floor using RTI, instead prioritising the completion of a full photogrammetric survey as well as laser scanning.

Once all target areas were photographed, the photograph sets were processed using RTI Builder, software developed by a team at the Universidade do Minho [1]. Images were first transferred from the camera to a computer and converted from RAW to JPEG format. Each individual image was checked for errors, with problematic ones removed, then all remaining images were loaded into RTI Builder. Next, the area of each image containing the reflective spheres was selected, and using this, highlights from the light source could be automatically detected to determine light source direction. The RTI model was then built using Polynomial Texture Mapping (PTM) fitter, using a HP Labs algorithm. Next the model was checked for errors and the tracing floor surface was explored using RTI Viewer. Here, the direction of light is adjustable in order to highlight surface texture detail. Different rendering modes were explored to ensure as much surface texture as possible could be viewed. The most useful ones were 'default', which tries to faithfully represent the object under directional lighting conditions, 'specular enhancement', where the floor surface appears to be wet giving a reflective surface sheen (colour can also be disregarded here as at times it can be distracting), as well as 'normals visualisation', a single static image with no adjustments, where normal vectors are rendered as colours (figure 5).

Laser scanning

Our third survey method was laser scanning, which we tested for both the tracing floor as well as the cathedral and cloister vaults. We used a Faro S 150 and for the tracing floor survey selected its highest settings of 1/1 resolution and 8x quality, giving a scan time of two hours and a resulting point cloud of over 20 million points. We wanted to see whether the laser survey could record the lines and curves of the plaster surface using these settings. We only had time to produce a single scan for this test and additional scans would likely have helped to produce a better 3D model. However, it is unlikely that this would have had a major impact on the recording of lines and arcs on the tracing floor surface, as they are often too fine to be detected by laser scanning.

Once processed, we produced a both a 3D mesh model and point cloud to interrogate the tracing floor surface. The results were poor even at the highest settings, with individual scratches on the plaster surface being very difficult to see, except for some of the larger ones. A similar experiment by Guidi et. al. (2014) produced better results, however, their target object had much greater surface undulations than the tracing floor. The photography and resulting orthophoto of the tracing floor, however, was better than expected, yet were still not as clear as the results from photogrammetry. Consequently, we focussed our tracing floor findings on the photogrammetry and RTI outputs. Nevertheless, laser scanning provided an excellent method of capturing the ge-

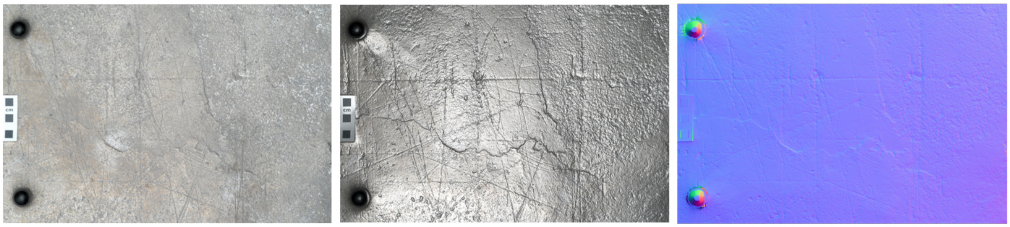

Figure 5
Processed images in RTI Viewer showing 'default' (left), 'specular enhancement' (middle) and 'normals visualisation' (right).

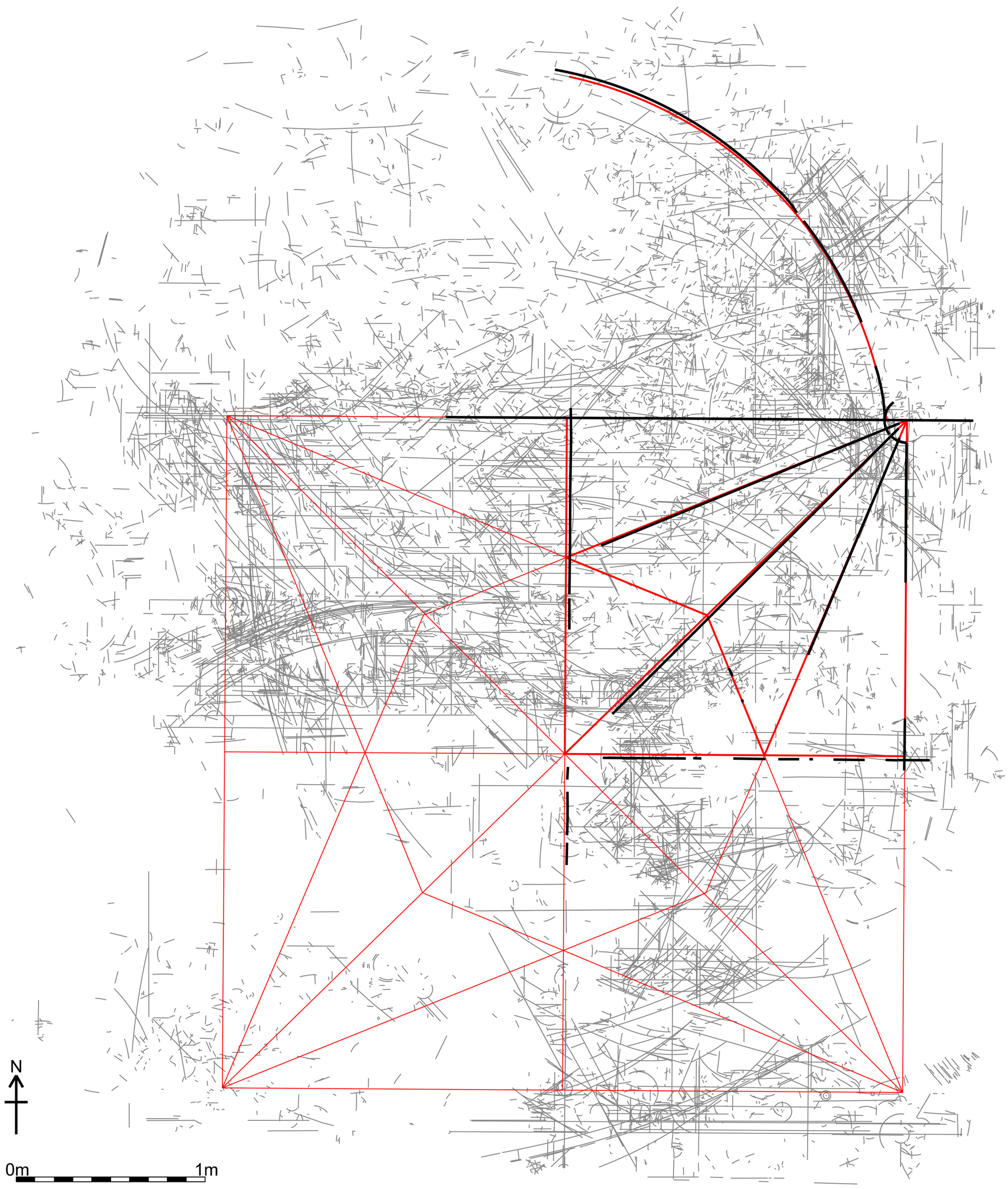

Figure 6
Digitally retraced lines and arcs of the tracing floor (grey) with east cloister inscribed lines highlighted (black). Hypothesised 2D bay design and 3D arc overlaid (red).

ometry of the vaulted ceilings, the methodology of which we have previously described in detail (Webb and Buchanan 2017).

RETRACING THE TRACING FLOOR

In comparing the three survey methods, photogrammetry and the resulting orthomosaics in particular provided the clearest and most comprehensive record of the tracing floor. To begin this manual retracing process, orthomosaics were first imported as TIF files into MicroStation V8i. The orthomosaics exported from Metashape were at a high resolution due to the necessity to include as much detail in the image as possible, resulting in large file sizes that could slow down the tracing process in MicroStation. Therefore, these orthomosaics were tiled on export and arranged in the correct location on import into MicroStation using georeferencing.

The drawing was set up by first producing a 0.5m grid over the orthomosaics to enable a methodical and detailed tracing of grid tiles individually, the same way that a site grid is used on archaeological sites. Traced lines were added as a separate layer, as well as the centres of arcs. Each tile was searched in turn, starting at the south west corner and proceeding left to right and row by row. When a straight line was found, it was traced using the 'Place Line' command. When a true arc was found, it was traced over using the 'Place Arc' command, set to 'Start, Mid, End'. Where curves were found not to be straight or a true arc, the 'B-spline by Points' command was used. Using a combination of these commands, sometimes based on trial and error, we were able to fully retrace the floor (figure 6).

Although we were able to trace more lines than those previously found in analogue surveys, the data was still problematic, in part due to varying image quality from the photogrammetric survey. Some curves were clear, sharp inscriptions on the surface, but these could be partially obscured by lower image quality or lighting. Other curves appeared as a less-clear surface abrasion of some kind, perhaps smoothed down over time to leave a duller surface. Other marks include light 'scars' on the surface, perhaps caused by age or water damage. Additionally, the plaster floor includes cracks that have appeared over time, which can sometimes be confused with inscribed markings if they are straight or arced in nature. The opposite issue also occurred, where lines or arcs appeared to have broken open to form a crack, perhaps the result of moisture damage. Therefore, judgement calls had to be made of whether to redraw in these cases or not. Our next phase of digital tracing will review these curves to account for levels of certainty in the data.

Next, to test the effectiveness of RTI, we traced over one target area (0.3 x 0.2m once the reflective spheres and scale bar were cropped out) and com-

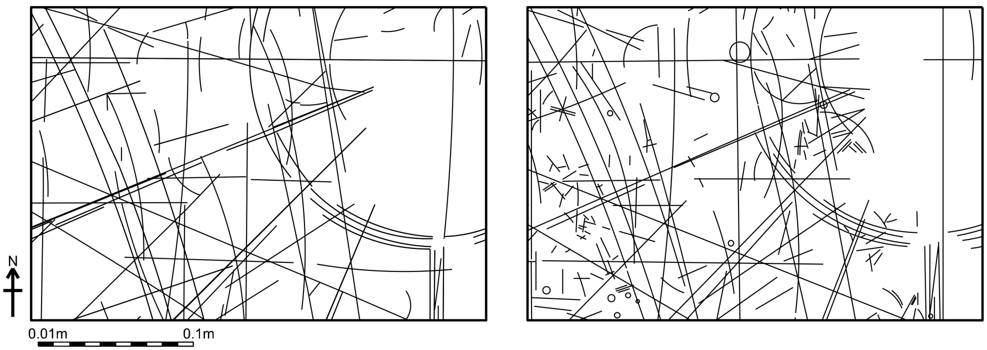

Figure 7
Sample area comparing tracing over the photogrammetry generated orthomosaic (left) and RTI export (right).

pared it with that already traced using photogrammetry. The RTI tracing process was similar to that of the photogrammetry orthomosaics: a jpeg image of the RTI model set to ‘specular enhancement’ was imported into MicroStation, a grid was overlaid and each square systematically traced over. The main difference was having to toggle between MicroStation and RTI Viewer to change settings and move the simulated light source. Comparing this with the photogrammetry generated equivalent revealed that more detail was found (figure 7), however, this may have been as the tracer was working on a smaller area, compared to the photogrammetry generated version which covered the entire tracing floor. Nevertheless, the sample area does suggest that more detail can be found using the RTI process, and it will be useful when attempting to pinpoint specific geometry, such as an arc centre point that cannot be found using the photogrammetry generated orthomosaic. In this example, we could then use the RTI method to scrutinise specific areas in greater detail.

COMPARING THE TRACING FLOOR TO THE EAST CLOISTER WALK

The last attempt to analyse the tracing floor was made by Pacey as part of an extended study of medieval architectural drawing (Pacey 2007). This research was conducted using the existing drawings and photographs of Harvey, comparing them with new tracings of selected parts of the floor. Pacey identified two groups of lines with specific architectural features at Wells. The first was a window from the east walk of the cathedral cloister; the second, a half plan of the vault above it. Whilst Pacey did attempt to confirm this using analogue measurements, he also suggested that testing his hypothesis would require more precise surveys of the floor and cloister. Our research attempted to answer this call through the use of digital surveying techniques.

Analysing the 2D plan

Laser scanning of the cloister was conducted with a 1/4 resolution and 4x quality, giving a scan time of approximately 15 minutes per bay. The results were processed using Faro’s proprietary software, producing detailed mesh models of its vaults. A run of three bays was selected from the east walk of the cloister, which we have designated E6 to E8 (figure 2). The models of these bays were then exported into Rhinoceros 6, where the intrados lines of their ribs were retraced using the ‘Section’ command. Using the ‘top’ view, the lines of the longitudinal and transverse ribs were extended with the ‘Polyline’ command and their points of intersection forming the corners of the plan were located on a horizontal plane, enabling measurements of each bay.

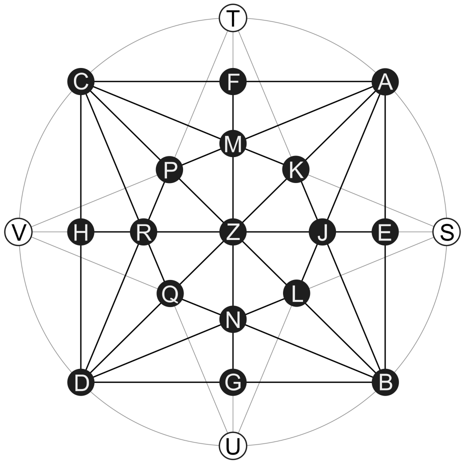

Figure 8
2D Hypothesis

Whilst the plans of these vaults (figure 8) are usually identified as square, in reality they are slightly rectangular, with an average width of 3.631m across their transverse sides (AC, BD) and 3.549m across their longitudinal sides (AB, CD). These were compared with the dimensions recorded from the digitally retraced tracing floor (figure 6). Though the half plan laid out on the floor is fragmentary and many of its lines are intermittent, the dimensions of the upper quadrant can still be reconstructed in some detail. The resulting quarter plan measures 1.779m on the north side at the base of the window tracery and 1.799m on the east, which presumably corresponds to the transverse side of the vault. These dimensions would give lengths of 3.558m for the window side and 3.598m for the transverse side, providing close matches for those recorded in the actual vault. This indicates that the disparity in dimensions in the cloister's plan, being slightly rectangular rather than true squares, was not just an accidental product of the construction process, but a deliberate choice which had been taken into account during the planning process.

With the plan of the vaults measured, it is possible to develop and test hypotheses for how it was laid out by masons. Our assumption has been that it was produced at a 1:1 scale in 2D, either on a dedicated tracing floor or some other available flat surface. Analysis of the cloister bays at Wells has revealed that the 2D geometry of their plan could potentially have been laid out using the 'starcut' method, a geometrical proportioning device as named by Stewart (2009) and further investigated by us, notably as a 'circle starcut' variation (Buchanan and Webb 2017). The rectangular plan of the bays is laid out, measuring 3.558 x 3.598m. Diagonals are drawn from corner to corner (AD, BC), then a circle is drawn centred on the middle of the bay (Z), with a radius extending to corners A, B, C, D. Further lines are drawn through the midpoints of each of the bay's sides, quartering the vault and its enclosing circle through E, H and F, G. The intersections between these lines and the outer circle (S, T, U, V) are then connected to bay corners forming chevrons (AUC, AVB, CSD, DTB,) creating the 'circle starcut'. This geometrical figure allows the vault to be divided into any theoretical set of proportions based on the dimensions defined by the outer circle. Tiercerons AJ, AM, BJ, BN, CM, CR, DN, DR are added using this starcut geometry, and finally the central octagon JLNQRPMK is added by connecting their crossing points. This hypothesised 2D geometry was then superimposed on the plans of the vaults themselves, showing a close match between theoretical model and reality.

Yet whilst this model can reproduce the lines of the actual vaults, this does not necessarily mean that it was the exact method used by the medieval masons. Unlike our other sites, the tracing floor at Wells gives us an unparalleled opportunity to test our methods directly against medieval design practices. Overlaying our theoretical model on the tracing floor produces a close match between model and reality (figure 6), but the results raise more questions than answers. Construction lines which we would expect to find are not present, and of the starcut there is no trace. This is strange because there is ample evidence that several aspects of the vault's design were still being worked out at full scale. Alternative angles are visible for several of the ribs, numerous test lines were drawn for the transverse side of the bay and a series of concentric circles can be found revealing the potential springing points.

Analysing the 3D design

Once the 2D geometry of the vault had been laid out, its 3D geometry was explored. The ribs were digitally traced from our 3D mesh model of the cloister and their curvatures quantified using best fit arcs following the lines of the trace. By measuring the radius, apex height and centres of these arcs, it is possible to identify the geometrical methods which could have been used to create them. For the cloister's east walk, it was discovered that all of the ribs were laid out using a fixed radius. Its recorded values range from 2.075-2.357m, with an average of 2.149m and a standard deviation of 0.064m. The method for applying this radius to each of the ribs was relatively straightforward. The rib's maximum height and length on the plan are defined, allowing its springing point and apex to be identified (figure 9, blue crosses). A circle of the fixed radius is drawn centering on both the springing point and the apex (figure 9, green circles), their point of intersection providing the centre for the rib (figure 9, red cross). An arc of the fixed radius is then drawn from this centre, passing through both the apex and springing point (figure 9, red circle).

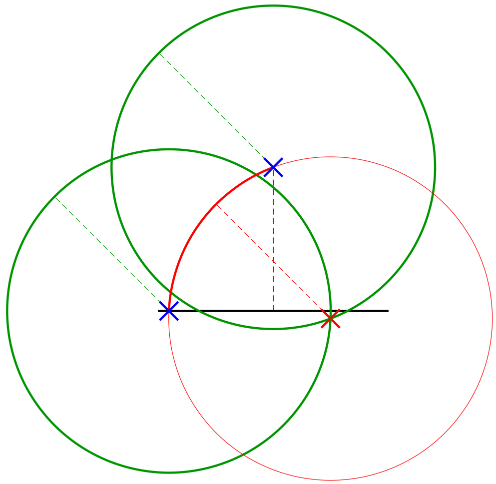

Figure 9
'Three circles' method of calculating the missing arc centre.

The only rib shown on the tracing floor is the wall rib relating to the window (figure 6). Whilst there is no sign of any construction lines relating to the method described above, the radius of this arc is exactly 2.151m. This is an exceptionally close match for the average in the cloister's east walk and it is therefore plausible that the radius for the vault's ribs was derived from the design of the window. This could be some indication of why none of the other ribs were laid out on the tracing floor. Once the radius had been established there was no further need, as the same curvature could be applied to all of the stones being cut for the vault ribs.

REFLECTIONS AND CONCLUSIONS

Testing different survey methods showed that photogrammetry is the best technique in the situation described. As 3D digital models derived from photogrammetry and laser scanning proved unhelpful, we will test structured-light 3D scanning, such as an Artec Leo, at future sites. RTI will continue to be used, particularly where a high level of detail is present, to allow greater forensic investigation. Virtual RTI, in which an existing 3D model is rendered with the light source changed to multiple positions around a target area, will also be explored. We will also investigate the use of pattern recognition and machine learning as potential methods of automating the tracing process, both for the 2D floor and 3D vault ribs.

At Wells, we will continue to study the geometry of the tracing floor to look for further matches beyond that suggested in the east cloister, as we have the entire east end of the main cathedral digitally surveyed. Our first investigation will focus on the ogee arches that can be found in the corners of the tracing floor survey, as well as the window tracery. We also hope to extend our surveying of floors to the Chapter House at Wells cathedral, and other sites such as York Minster and Bourges cathedral.

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