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Geospatial Imaging

Carlisle Castle, Cumbria
A Geospatial Survey of Historic Carvings and Graffiti

Li Sou

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CARLISLE CASTLE
CUMBRIA

A GEOSPATIAL SURVEY OF HISTORIC CARVINGS AND GRAFFITI

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SUMMARY

Carlisle Castle situated in Carlisle, in the county of Cumbria, originated in the 12th century and was in use as a military base for 900 years. Many renovations and additions to the castle complex were made over time, and as such, a palimpsest of modifications can be found throughout many of the castle's structures. Reflecting these changes through time are the carvings and graffiti that are scattered over the site. Prior to this project, many have never been officially recorded, and none of them have been surveyed using modern laser scanning and Structure from Motion (SFM) photogrammetric techniques. A programme of recording was undertaken by Li Sou, CIfA Specialist Placement in Geospatial Investigation Techniques, and Paul Bryan, Geospatial Imaging Manager. Within the castle keep a series of reliefs, known as the Prisoners' Carvings, and a medieval door covered in etchings, were laser scanned, photographed and filmed. The datasets were then compared to examine the detail and quality of their outputs, to determine each technique's suitability for recording such historic carvings. Additionally, photographic recording for SFM photogrammetry was undertaken for a Roman altar stone, medieval and post-medieval graffiti and carvings across the castle complex, to produce 3D models as a record of their current condition.

CONTRIBUTORS

The geospatial survey was undertaken by Li Sou and Paul Bryan, of Historic England's Geospatial Imaging team. Li Sou, with the help of Jon Bedford, Senior Geospatial Imaging Officer in Historic England's Imaging team, processed the laser scan point data for mesh generation and digital imagery for Structure-from-Motion photogrammetry. PTM models were generated by Andy Crispe, Graphics Officer in Historic England's Imaging team. Li Sou conducted the data analyses of the project with additional comments from Jon Bedford and Paul Bryan. Unless stated otherwise, the images used in the text were produced by the author.

ACKNOWLEDGEMENTS

The author would like to thank Dr Mark Douglas and Sally Wilson, of English Heritage Historic Properties Curators team, for arranging access to the survey areas of the castle and aiding in the identification of historic carvings and graffiti. Many thanks also to Jack Glauser of JMG Scanning Services, for registering the laser scan data.

ARCHIVE LOCATION

The report has been deposited at the Historic England Archive, The Engine House, Fire Fly Avenue, Swindon.

DATE OF SURVEY

The surveys took place between 15th and 17th February 2016.

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PART 1: THE PROJECT

INTRODUCTION

From 15th-17th February 2016, a non-invasive survey was undertaken of historic carvings across the site of Carlisle Castle, by Li Sou, CIfA Specialist Placement in Geospatial Investigation Techniques, and Paul Bryan, Geospatial Imaging Manager. A Leica P40 terrestrial laser scanner was used alongside a Canon 5D MKII DSLR camera to take still photography and film recordings for Structure from Motion (SFM) photogrammetric processing. This report documents the results of the analyses carried out using the different geospatial imaging techniques and details findings revealed from the outputs generated. The results highlight which methods of non-invasive metric survey technique are most applicable to such *in situ* stone carvings, for the purpose of maintaining a record of their present condition and providing further scope for detailed archaeological analyses of the carved features.

The project was undertaken as part of the placement holder's training programme with the Geospatial Imaging team at Historic England, and was conducted as a response to a service request from the English Heritage Curatorial Team to examine previously unrecorded historic graffiti identified on site. 3D laser scanning took place at resolutions of either 3.1mm or 1.6 millimetres at 10 metres (in this report referred to as 3.1mm and 1.6mm resolutions). This means where the scanner is located 10m away from the target scan face, it will record a point every 1.6mm or 3.1mm. As the laser scanner was in reality placed substantially closer to the target scan areas, being at most 2m away, the resolutions collected were in reality recorded at a sub-millimetre resolution.

The scans of a medieval oak door also featuring medieval carvings were recorded in both high and normal sensitivities, to compare the data quality of these setting variations (figure 1). In addition, a 3D laser scan survey was conducted of Room 22 within the keep, believed to be a prison cell, which is covered in carvings of medieval date and known colloquially as the "Prisoners' Carvings" (figure 2) (Summerson 2008, 19).

Photography was used to produce SFM photogrammetric models of previously unrecorded carvings throughout the castle complex, to use as a record of their present condition, in addition to providing a means of comparing the quality of data captured using this method to that obtained from the laser scans. Video recording was conducted within the prison cell room and stills extracted from the footage, as a further comparison of the data quality taken from this quicker data capturing approach.

The 3D point clouds generated from the different recording techniques were analysed for variations in their quality and detail, to determine which methods and settings are most appropriate for the recording of historic graffiti. In addition, an archaeological analysis was conducted of some of the carvings within the prison cell and wooden door, to provide a better understanding of their history and chronology. This was done using meshes produced from the raw point cloud data. After this, a comparison was made between the meshes and point clouds, to determine to what extent wrapping points in a mesh alters point positions, and how this in turn affects the 3D imagery generated.

Figure 1: Medieval door covered in carvings, originally the door into the so-called prison cell room.

Figure 2: Section of the Prisoners' Carvings, in Room 22 of the keep of Carlisle Castle. The boar is the badge of Richard III, a fetterlock is to its right. The fishes may represent dolphins, the emblem of the Greystoke family (Summerson 2008, 19). On the right, an earlier carving of an antlered deer has been carved through by later images of a rose, scallop and three fleur de lis. Image source: English Heritage 2016.

ESTABLISHING THE PROJECT

English Heritage Properties Curator Team Leader, Dr Mark Douglas, requested a detailed investigation into historic carvings at Carlisle Castle, in conjunction with a study of the sandstone panel above the castle's outer gatehouse entrance, prior to its replacement in spring 2016. Previous stereo-photogrammetric recording was conducted by the Geospatial Imaging team of Historic England, then English Heritage (2011); however SFM photogrammetry and the use of video recording as a means of data capture had yet to be trialled. As such, the team manager, Paul Bryan, requested the placement holder to investigate the carvings using a variety of geospatial imaging methods, as a means of comparing all available approaches, to determine the most suitable means of recording such historic features.

CONTEXTUAL BACKGROUND

Carlisle Castle, situated in Carlisle in the county of Cumbria, dates from the 12th century, and had been in use as a military base for 900 years (McCarthy, Summerson and Annis 1990, 8). Built on the site of a Roman fort, it was strategically situated in a position where roads to Scotland and across northern England meet, and had always been occupied by soldiers throughout the duration of its use (Summerson 2008, 3). Roman stonework was reused in the construction of the medieval castle, and a striking example can be seen inside the gatehouse tower, where a third-century altar, dedicated by a Syrian soldier serving in the 20th legion, was re-carved into a door lintel and set sideways (figure 3). Many renovations and additions to the castle complex were made over time, and as such, a palimpsest of modifications can be found throughout many of the castle's structures. Reflecting these changes through time are the carvings and graffiti that are scattered over the site.

Figure 3: Roman altar stone. Orthophoto produced from SFM photogrammetry. Image has been rotated as it was previously used as a door lintel.

THE PRISONERS' CARVINGS – A BRIEF HISTORY OF RESEARCH

The Prisoners' Carvings are located on the second floor of the keep. They cover the north and south walls, the sides of two doors and the part of the window embrasure in the east wall of a small rectangular room with a vaulted ceiling, defined as Room 22 in English Heritage's architectural inventory of the site (McCarthy, Summerson and Annis 1990, 83). More carvings are located in Room 21, a mural chamber, at the end of the room closest to Room 22, and on the original oak door to Room 22, currently on display in Room 17 beside its original location (see figure 1).

Whilst they are commonly known as the Prisoners' Carvings, there are conflicting accounts as to whether the Keep was ever used to house prisoners during the time from whence the carvings are thought to date. Early guides at the castle considered the carvings to be the work of Scottish soldiers imprisoned during the 18th century, but Field refuted against this interpretation, being the first to state that they must be significantly older due to the heraldic subject of many carvings (Field 1937, 13). In contrast, the English Heritage architectural inventory of the site describes Rooms 21 and 23 as "the Prison Rooms", with Room 23 being the prison (McCarthy, Summerson and Annis 1990, 83). However, the function of Room 21 is stated to be an oratory, or private chapel (ibid). The upper floors of the keep are not mentioned in records to have ever been used to hold prisoners, and it is debatable whether a prisoner would be permitted the use of a chisel (ibid, 169). Although the use of the rooms and the identity of the carvers are not known, the popular name for the carvings will be used throughout this report to provide consistency.

A hand drawn visual survey of the Prisoners' Carvings and those covering the medieval door was conducted by H. G. Wills, who interpreted and identified some common themes in the imagery; heraldry, hunting, religion, medieval armour, warfare and weaponry, nude female figures and non-specific (2015, 53). The most prolific carvings, those of heraldic badges, were first interpreted by Field, who determined that they were the work of a single carver due to their similarity of style, allied to the Yorkist cause during the War of the Roses in the 15th century, on the basis of symbols representing Richard of Gloucester (the boar), and his supporters the Dacres (the scallop shell) and Percys (the fetterlock) (1937, 13, 21). Additionally, specific styles of medieval armour are all indicative of the late 15th century, allowing certain carvings to be more securely dated (McCarthy, Summerson and Annis 1990, 169) (Figure 4).

Summerson interpreted some imagery as coming from folklore, such as mermaids holding mirrors – a traditional symbol of vanity, and a fox preaching to chickens, and suggests the carvings of nude females indicate that the castle was largely occupied by men (McCarthy, Summerson and Annis 1990, 169). The religious themes of some carvings, including images of the crucifixion and St George and the dragon, may indicate a member of the clergy had created some of the carvings, as a chapel was located in the 'royal' area of the keep, whilst the heraldry and warfare scenes suggest a carver with a military background (Summerson 2008, 19).

Figure 4: Carving of a soldier wearing a helmet, of a style dating to the 15th century.

On closer observation of the carvings, it is clear that they are palimpsest of different works over time, with older carvings being obscured by later, more deeply etched ones (see figure 2). Wills assigned dates to the carving schemes based on his interpretations, ranging from the 10th to 16th centuries (2015,136-45). The earliest graffiti appears to feature animals of the hunt and arrows, and much has been carved over in several areas by later markings. Notably, the wooden door that was originally set into one of the side rooms also features similar carvings, and this was surveyed using the same techniques as for recording the Prisoners' Carvings, to determine if they are indeed stylistically similar.

Some of the later graffiti across the castle complex can be attributed to the soldiers of the 34th Cumberland and 55th Westmorland regiments (later amalgamated as the Border Regiment), who had been stationed in the castle from 1873 until the depot closed in 1959 (figure 5). Although particular aspects of some carvings can provide clues as to when they were produced, many are more enigmatic and of uncertain date. As such, with the assistance of Mark Douglas, senior properties curator for English Heritage, several instances of historic graffiti were identified and photographed for SFM photogrammetry.

Figure 5: Carved graffiti produced by a soldier of the 55th regiment of foot, based at Carlisle Castle.

Whilst the Prisoners' Carvings were previously surveyed using stereo-photogrammetric techniques conducted by then English Heritage's Metric Survey team, many others scattered across the site have never been officially recorded, and none of them have been surveyed using modern laser scanning and SFM photogrammetric techniques. As such, a programme of recording different carvings around Carlisle Castle was undertaken.

PART 2: VISUALISATION AND ANALYTICAL TECHNIQUES

METHODOLOGICAL CONTEXT

As the previous section has highlighted, much of the historic graffiti and carvings across the site of Carlisle Castle have yet to be officially recorded and studied. Certain significant panels, such as the Prisoners' Carvings, had been surveyed previously using stereo-photogrammetry by English Heritage's Metric Survey team, for reasons of stonework decay and a lack of existing records (English Heritage 2011), however neither laser scanning or modern SFM photogrammetric techniques have previously been used. With consultation from English Heritage curators, it was deemed appropriate for the placement holder to conduct a comparative study in using these geospatial imaging techniques, with the intention of producing detailed datasets of the Prisoners' Carvings and the medieval door and analysing the level of detail and quality of imagery produced by each. SFM photogrammetry was deemed an appropriate method of recording other historic carvings across the site, and all 3D models and images were archived with Historic England.

Laser scanning

Laser scanning was undertaken using a Leica P40 terrestrial ScanStation (see Appendix 1 for specifications). The scanner was positioned in different locations to collect adequate point cloud coverage of the Prisoners' Carvings and medieval door at different angles, and the scanner was set to record in a local coordinate system only (figure 6). To scan the medieval wooden door, an initial 360^0 scan was undertaken of the door's complete surroundings, at a resolution of 3.1mm. Two detailed window scans of only the door area were then taken, both at a resolution of 1.6mm, but set to either normal or high sensitivity, for comparison of these different settings. The laser scans of the Prisoners' Carvings room interior were all 360^0 laser scans at a resolution of 3.1mm, with normal sensitivity, however the point clouds generated of this area were all combined when the scan data was imported into Leica Cyclone software, where it was registered together on the basis of ground targets placed in each scan in the field. This processing was conducted by Jack Glauser, of JMG Scanning Services. In Cyclone, all point clouds were cropped to only the areas of comparative analysis, and then exported either as PTX or PTS files.

Figure 6: Leica P40 laser scanner set up to scan the medieval door.

SFM photogrammetry using still photography

Still photography was taken using a Canon EOS 5D mark II, 21.1 megapixel full frame DSLR camera, with a wide-angle fixed prime 24mm lens on aperture priority setting, attached to a tripod, fitting Historic England's Metric Survey criteria for digital cameras (Andrews, Bedford and Bryan 2015). SFM photogrammetry ideally requires evenly balanced lighting, however, such conditions were lacking in many areas of the castle (figure 7). Whilst three-point lighting or the use of stronger artificial lighting would have provided more balanced lighting over the entire survey area, the confined area of the Prisoners' Carvings limited the lighting options available on site. As such, a two-point lighting solution was used to light each shot. One LED light panel was attached to the camera, acting as the key light, whilst a separate LED panel was held from a different position by a separate operator to provide a fill light. In areas where lighting was particularly poor, two extra LED panels were arranged on tripods to provide further fill light.

For the Prisoners' Carvings, each wall face (northwest, southeast, southwest and northeast) was completely recorded in a series of overlapping photographs, saved in maximum resolution RAW format. The faces were given arbitrary numbers to uniquely identify each throughout this project. Figure 8 shows the location of the Prisoners' Carvings room within the keep. Each wall face was grouped into separate Agisoft Photoscan projects for processing.

Figure 7: DSLR photography of recently discovered historic graffiti outside the Captain's Tower, for SFM photogrammetry. Note the bright raking sunlight on the wall surface.

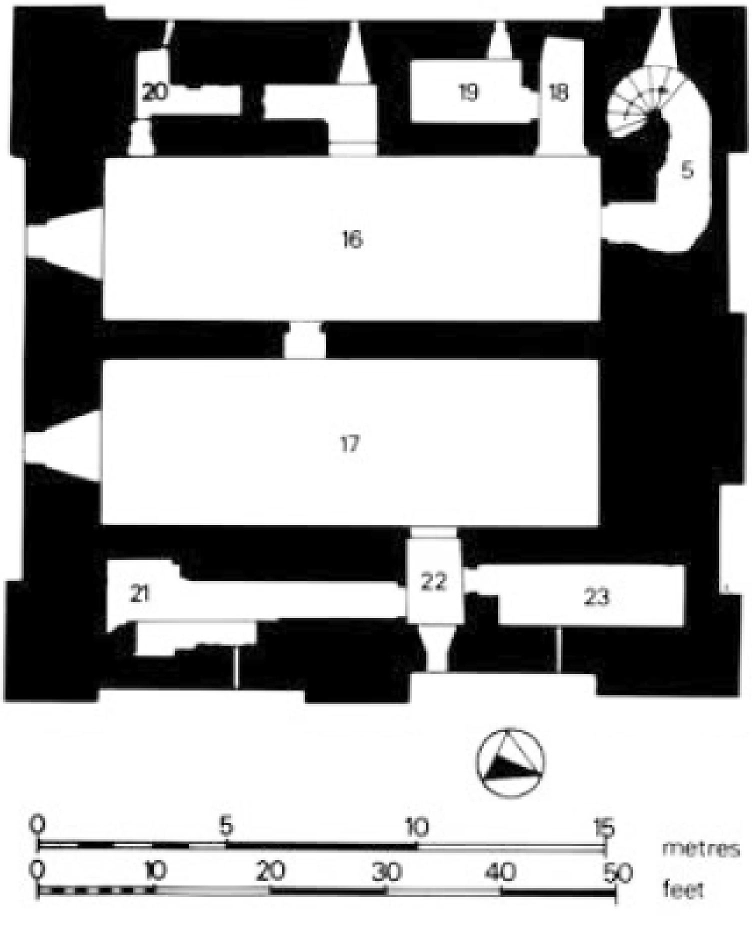

Figure 8: Plan of the second floor of the Keep at Carlisle Castle. In English Heritage's 1990 survey, the Prisoners' Carvings room was labelled as room 22. The wooden door is currently displayed on the southwest-looking wall of room 17, to the right of the entrance to room 22. Image source: modified from McCarthy et al, 1990, 77.

For other carved features in the castle, only the carved areas were recorded in overlapping shots, although their location is included in the photographic metadata for archiving. A scale bar and colour reference scale were included in the initial and final shots of each feature, to allow for post-processing colour calibration.

Colour and exposure correction of the captured RAW images took place using Adobe Camera RAW to ensure all images maintained the correct colouration of the stonework as seen by eye on site. The images were grouped into different projects on the basis of different sections of carvings or graffiti, and converted into TIFF format for SFM processing in Photoscan, where the scales were digitally added. Additionally, masking of non-relevant details within all photos was required to avoid extraneous points being generated, which can substantially increase processing time.

In order to scale and align the SFM datasets to the same local coordinate system as used in the laser scans, 10 coordinate points were exported from the laser scan point cloud of each of the study areas These were placed as markers in Photoscan to aid in the initial point alignment of the photography (Appendix 2). Full technical details of the set up used can be found in Appendix 3, however to ensure data quality was sufficient, only markers with alignment errors below 3mm were used in the final SFM processing, to follow Historic England's metric survey specifications (Andrews, Bedford, Bryan 2015). The dense point clouds of the Photoscan projects were cropped to only the areas to be analysed, and then exported in PLY format, for further detailed analysis using CloudCompare.

SFM photogrammetry using video recording

Whilst still photography is the standard source of images for SFM recording, it is possible to extract film stills and produce 3D models from such data. To investigate the capabilities of this technique, the Canon 5D DSLR was also used in movie capture mode to test the quality of video imaging SFM photogrammetry that the camera can produce. The camera was mounted to a Manfrotto Fig-Rig, a hand-held video-recording stabiliser, to reduce shakiness of the footage.

The lighting set-up was not changed from that of the still photography, however the motion of the camera required the fill light operator to follow the cameraperson as they panned across the surface of the carvings, moving slowly from the top of each wall, panning sideways then downwards towards the bottom. Each wall of the Prisoners' Carvings was recorded in separate videos, in addition to a video of the medieval door. The video stills were extracted using VLC Player's still extraction feature, with the footage playback slowed down to 0.50 speed, with every 24th frame recorded.

Images were saved as JPEGs, as the write speed of the video player was not able to process TIFF format imagery to match the speed of the video playback. Upon extraction, the overlapping video stills were processed in Photoscan using the same method detailed above for the still photography, using the same imported laser scan coordinates, and dense point clouds were produced.

METHOD OF DATA COMPARISON

Due to the time constraints of the project, it was decided that a comprehensive analysis of all graffiti and carved elements recorded in the survey was not possible. As such, two distinct areas of carvings; one from the Prisoners' Carvings room (figure 9), and one panel of the wooden door (figure 10), were chosen for study. For all laser scans, extraneous data was deleted in the working ModelSpace in Leica Cyclone, so only the study area remained.

Figure 9: Carved stone block from the northwest facing wall within the Prisoners' Carvings room

Figure 10: Carved dark oak wood plank of the original door to the Prisoners' Carvings room.

For the Prisoners' Carvings section, all of the point clouds generated from laser scanning this area within the room itself were viewed as a composite ModelSpace in Leica Cyclone and the point clouds were combined and exported as a PTS file. For the wooden door, the two laser scan point clouds taken at different resolutions were exported separately as two different point clouds in the default Cyclone PTX file format, so each point cloud can be opened separately to compare their levels of detail (Leica Geosystems 2015).

The dense point clouds from SFM photogrammetry were exported as PLY files, a flexible 3D polygon file format which is widely applicable in different mesh editing software (Turk 1994). The PLY, PTS and PTX files all hold the point cloud dot data similarly, therefore there should not be any stark differences due to the two different formats used.

Statistical comparison between point clouds

An initial statistical comparison between the laser scan and SFM point clouds was conducted, using CloudCompare, a 3D point cloud and mesh processing software that is designed to compare two 3D point clouds, or between point clouds and meshes. In this stage of the data analysis, it was possible to identify which point cloud dataset was better at recording the exact details of the medieval carvings' current appearance, to judge each record method both qualitatively in how the data reflected the recorded surfaces, and also quantitatively, in the number of points that were acquired using each method. To do this, a deviation analysis was visualised, to determine how different the carved surfaces are presented in the laser scan and photogrammetric point clouds.

Comparisons were made between:

- laser scan point clouds of different resolutions taken of a panel of the medieval door (3.1mmresolution, normal sensitivity, 1.6mm resolution, normal sensitivity and 1.6mm resolution, high sensitivity);
- laser scan point cloud and still photography SFM photogrammetry point cloud of a section of the Prisoners' Carvings;
- still and video photography SFM photogrammetry point cloud of a section of the Prisoners' Carvings;
- the effect of laser scan position and angle on recording quality of a section of the Prisoners' Carvings.

For point clouds without normal values, these were computed in CloudCompare, on the triangulation setting that is best suited for surfaces with curved elements. This was deemed appropriate for the curved details of the carvings. After this, the distances between the two point clouds were computed, to see how much they deviate from each other. The higher resolution/sensitivity point cloud was set as the reference, for the lower resolution/sensitivity point cloud to be analysed against. The Octree level was set to 10, as the recommended level for the two point clouds and the distance between the point clouds was computed. The compared point cloud's scalar field was then used to observe the scale of deviation between the two point clouds, using a colour scale.

Examining the carvings using 3D meshes

A second, more subjective analysis was required of the appearance of the data output as solid 3D models, to determine which dataset could reveal the most details within the carvings. In generating these outputs, it was possible to examine the carvings in more visual detail than is possible from studying the point clouds, particularly through the use of manipulating virtual lighting conditions to reveal greater detail on certain features. To do this, the raw point clouds were loaded into CloudCompare, where each dataset was meshed using the same settings.

3D meshes for the point clouds produced from laser scanning and still photography SFM were generated. As the video SFM point clouds were of low quality, meshes were not produced from those datasets for analysis. Normals were computed for the laser scan data in CloudCompare using the PCL wrapper normal and curvature estimation tool, as this information did not transfer from the Cyclone export of the scan point clouds. The Poisson surface reconstruction tool was used to generate the meshes, with the octree level was set between 11-15 to ensure meshes produced sufficient detail of the carved areas within a suitable length of processing time. Extraneous polygons were clipped and deleted, leaving only the sample study areas as meshes. These were saved as OBJ files (see results below for images).

The meshes were then imported into Autodesk 3DS Max, to generate virtual Polynomial Texture Mapping (PTM) models (also known as Reflectance Transformation Imaging, or RTI) by Andy Crispe, Graphics Officer at Historic England. Where file sizes were too large to import into 3DS Max unedited, the meshes were divided into segments, which were processed separately. The SFM dense point cloud of an area of historic graffiti located on the exterior wall of the Captain's Tower was also exported for virtual PTM, as it featured a carved date, which was considered significant by Dr Mark Douglas. Such models allow virtual light positions to shine over the surface of the meshed models, bringing out their surface relief details.

Due to the time limitations of the placement holder's project, it was decided that a comprehensive archaeological study of the historic significance of Carlisle Castle's graffiti was not possible. However, in examining the meshes and PTMs, it was possible to identify different carvings on the selected areas that were digitally processed.

Comparing the point clouds to 3D meshes

Lastly, the generated meshes were compared to the point clouds. It must be noted that to analyse meshes in CloudCompare, many of the programme's features can only be applied to the mesh vertices. This is the point cloud of interconnected triplets of points that compose the mesh's triangles (CloudCompare 2015). This comparison was significant as it examined the underlying changes that creating the mesh caused against the original laser scan or photogrammetric point clouds, determining how the data had been affected by such manipulation and emphasising how raw point clouds require substantial processing in order to produce outputs suitable for viewing and detailed study.

PART 3: RESULTS

DATA CAPTURE: SPEED, QUALITY AND PERFORMANCE OF TECHNIQUES

As this project's main focus is to compare the different methods of geospatial data capture and their quality, short overviews of the data acquisition process will be made for each technique used to record the Prisoners' Carvings and medieval door. The aspects evaluated are the time taken for recording, initial impressions on data and image quality and the appropriateness of the method in the castle.

Still DSLR photography for SFM photogrammetry

The Prisoners' Carvings were fully photographed over two hours, and photography for the wooden door took approximately 30 minutes. The tripod had to be adjusted frequently to frame each shot correctly on the uneven surface of the room inside the keep, in addition to ensuring each individual shot was lit suitably using the LED light panels. However, as a result of such quality assurances made on site, the resulting photography was sharp and required less manual colour calibration in post-processing.

Upon SFM processing of the TIFF files, the point clouds appear to be spatially aligned correctly, and the meshes produced have high polygon counts (table 1). The coloured texture of the Prisoners' Carvings appears quite dark in places. This was due to multiple lighting issues that were outside of the surveyors' control. A large window on the north east wall shone bright sunlight onto certain areas of the room, whilst a halogen light situated above the modern glass doorway into the Prisoners' Carvings room produced a strong artificial yellow light that substantially lit the ceiling and upper walls of the room. Whilst using the colour correcting tool upon creating the texture for the 3D model managed to counteract some of these effects, certain areas of the model remain darker than the rest, especially around corners (figure 11).

Photoscan project	Dense point cloud	Mesh polygon count
Prisoners' carvings north west facing wall	46,056,563	9,211,311
Prisoners' carvings north east facing wall	10,485,678	1,810,638
Prisoners' carvings south west facing wall	13,885,950	2,777,190
Prisoners' carvings south east facing wall	33,914,195	6,782,838
Oak door panel	24,209,634	4,841,926

Table 1: The number of points each SFM point cloud is composed of, and the polygon count of meshes after processing into 3D models.

Figure 11: Orthophoto of the northwest facing wall, generated from SFM photogrammetry taken from still DSLR photography. Note, the right side of the wall is darker where less light shone on these areas in the photos taken.

Video recording with DSLR, mounted on handheld stabiliser, for SFM photogrammetry

Using the DSLR video mode, all four interior faces of the Prisoners' Carvings room were recorded in under an hour, and the wooden door in less than five minutes. This was considerably faster than the taking of still photography, however the imagery captured was notably less sharp. This was due to the camera's lack of a video autofocus setting, so once the camera operator moved out of the manually set focal length, the video became out of focus. This was difficult to rectify, as the uneven floor of the room made it difficult to keep the camera aligned correctly as it moved.

It should be noted that this issue was specific to the Canon 5D used, as some other camera models do have video auto-focus features. Additionally, the image colours from the video footage were more adversely effected by the varied lighting mentioned above. The colour correction tool did not successfully balance out these issues, resulting in some stark lighting contrasts on the 3D texture (figure 12).

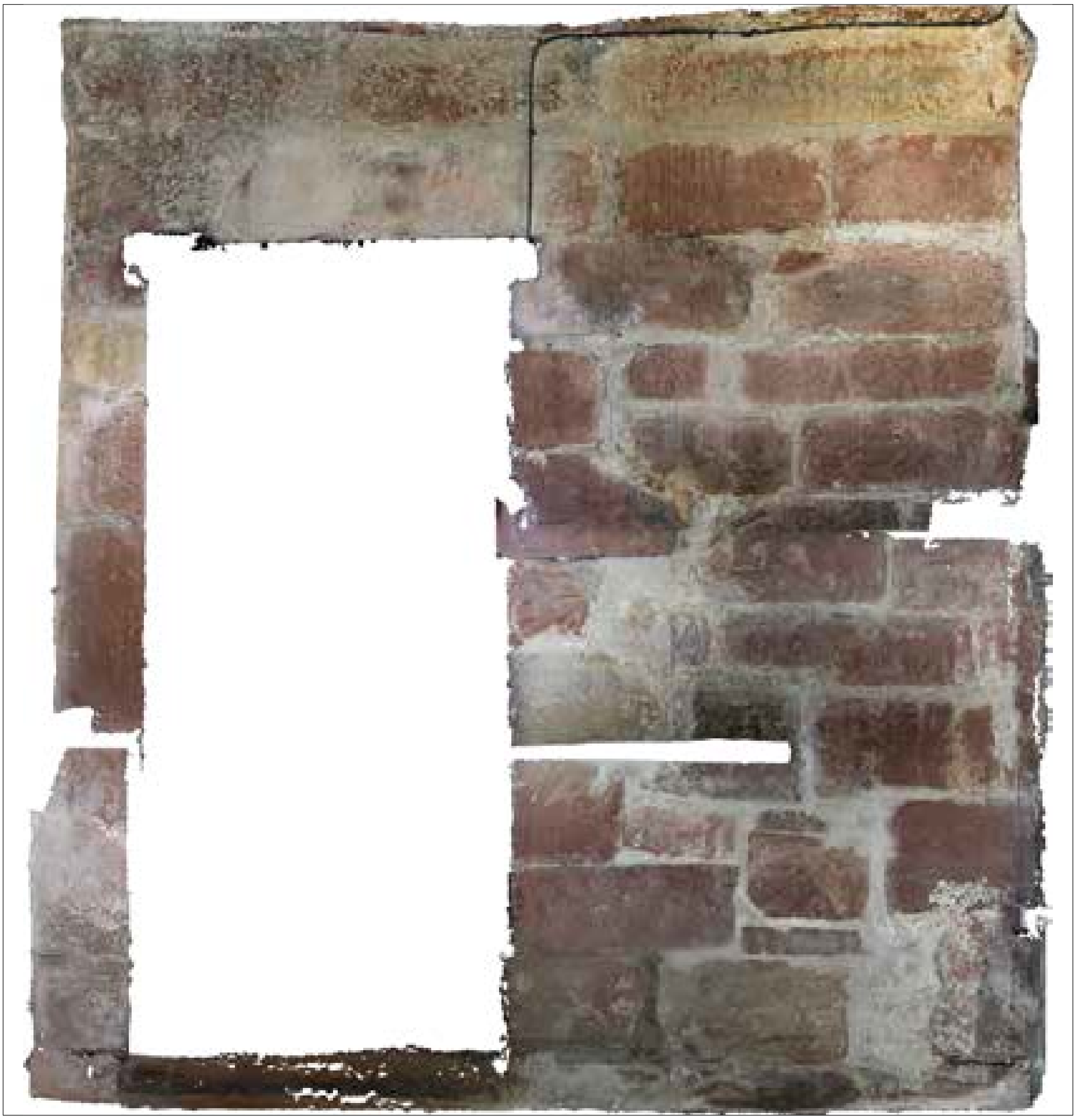

Figure 12: Orthophoto of the northwest facing wall, generated from SFM photogrammetry taken from video stills. Note the top right corner is coloured yellow from the halogen light above that area. The gaps in the wall were caused by a lack of imagery coverage in those areas.

Another problem emerged in that, despite the use of the handheld stabiliser, the motion in the footage was still not completely fluid, and motion blur occurred frequently. It is suggested that a gimbal camera stabiliser would be more effective at reducing such effects. However, the compact size of the room may make the operation of such stabilising equipment difficult, and it was not possible to acquire one for use in the time frame of the project.

It was found that the image quality was reduced upon extraction in VLC player, as the program could not write to TIFF format quick enough to work alongside the layback of the video footage. As such, the stills had to be extracted as JPEGs, which are low resolution. In addition to this, the automated extraction method did not always take enough overlapping still imagery of certain areas of the Prisoners' Carvings, resulting in some areas becoming misaligned and gaps appearing in the dense point cloud and mesh produced (see figure 12).

Despite these issues, the imagery still processed successfully in Photoscan, although it is very apparent that the level of detail in the mesh is not as high as that of the still photography (compared to figure 11).

Laser scanning with Leica P40

The 360⁰ laser scans of the Prisoners' Carvings and wooden door at 3.1mm resolution, set to normal sensitivity, took three and a half minutes, and the 1.6mm resolution window scan of the wooden door, set to normal sensitivity, took approximately three minutes. The window scan of the wooden door at 1.6mm resolution, set to high sensitivity, took approximately 12 minutes. In contrast to the P40's relatively quick laser scan speed, its imaging took a very long time with the HDR mode on, in some instances taking over 15 minutes to take enough photographs to fully cover a 360⁰ area. This was due to the varied and contrasting light sources within the keep, which caused the issues in texture appearance which are mentioned above. Additionally, the image quality was very poor and overexposed (figure 13).

In hindsight, imagery from the 360⁰ scans taken from the room the wooden door is situated in was not needed, however the laser scan data was highly beneficial in aiding in the registration and visual alignment of the different scans in Cyclone.

3D POINT CLOUD COMPARISONS – MEDIEVAL DOOR

The analyses conducted of the laser scans taken of the medieval door focussed on comparing the difference that different pre-set scan resolutions and sensitivities produced in the point clouds generated. In addition, the laser scan point cloud was compared to the dense point cloud produced using SFM photogrammetry.

Medieval door: 1.6mm normal sensitivity laser scan x 3.1mm normal sensitivity laser scan

Scalar fields were generated to examine the 3.1mm resolution laser scan against the 1.6mm higher resolution point cloud as a reference. Figure 14 displays the scalar field, which highlights areas of deviation between the two point clouds. It can be seen that all distance variations are below 1.185mm, with the majority being below 0.395mm. As such, the differences between the 1.6mm and 3.1mm resolution point

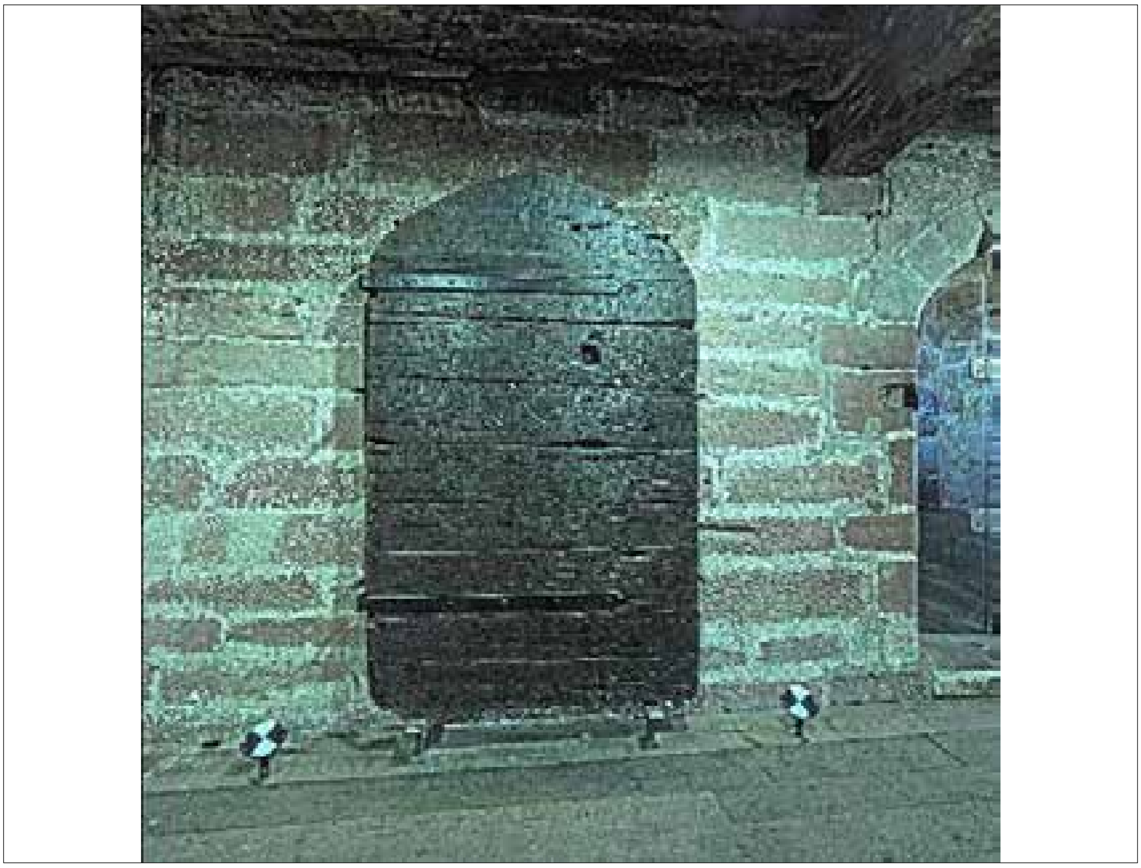

Figure 13: the overexposed appearance of the imaging taken from the P40 laser scanner

clouds are small. For the purpose of recording carvings on the wooden panels of the medieval door, both resolutions are suitable, but the 3.1mm resolution setting completes scans in a quicker time.

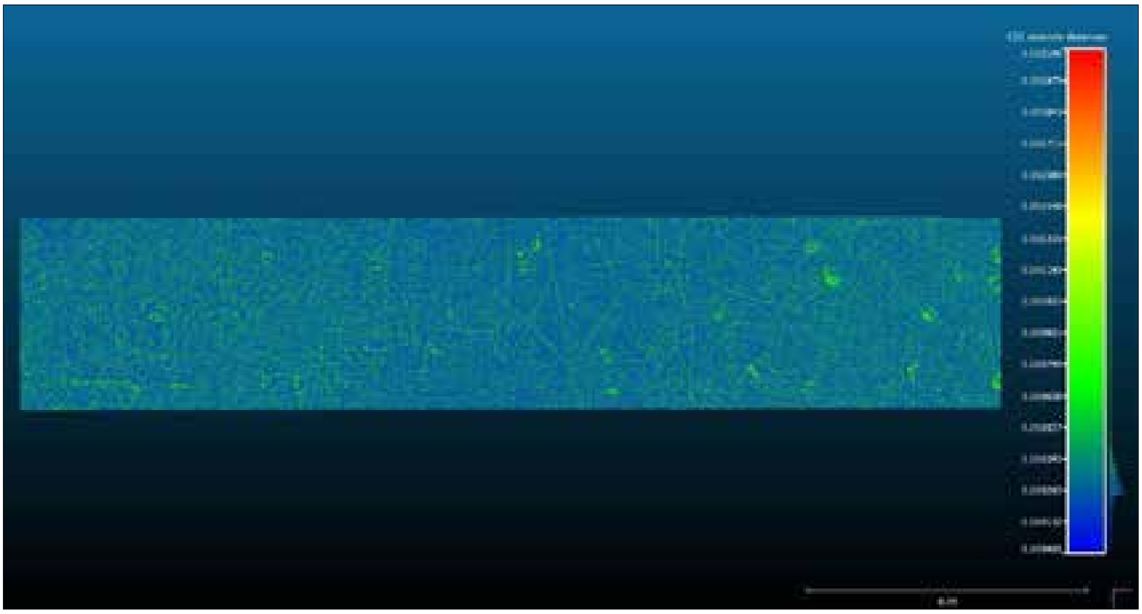

Figure 14: Scalar field of 3.1mm resolution laser scan of the medieval door point cloud. There are no distances of more than 1mm between this and the 1.6mm resolution point cloud.

Medieval door: 1.6mm resolution normal sensitivity laser scan x 1.6mm resolution high sensitivity laser scan

Scalar fields were generated to compare the difference between the high and normal sensitivity scan options on the Leica P40 laser scanner. Both scans were taken at 1.6mm resolution, and the high sensitivity scan point cloud was used as the reference for the normal sensitivity point cloud's scalar field to be compared against (figure 15). Examining this, it is clear that no points in the clouds are above 1.005mm in distance from each other and the majority have a maximum deviation of 0.274mm. These distances are even smaller than those of the 1.6mm resolution and 3.1mm resolution scans. Although all of these different resolutions and sensitivities do present point clouds that are not identical to each other, it is clear that the extent of the variation is very small, especially in changing the scanner sensitivity. As such, it can be suggested that scanning at high sensitivity is not essential in the recording of the medieval carvings at the castle, as it took four times as long to do (12 minutes) rather than use the normal sensitivity mode (3 minutes).

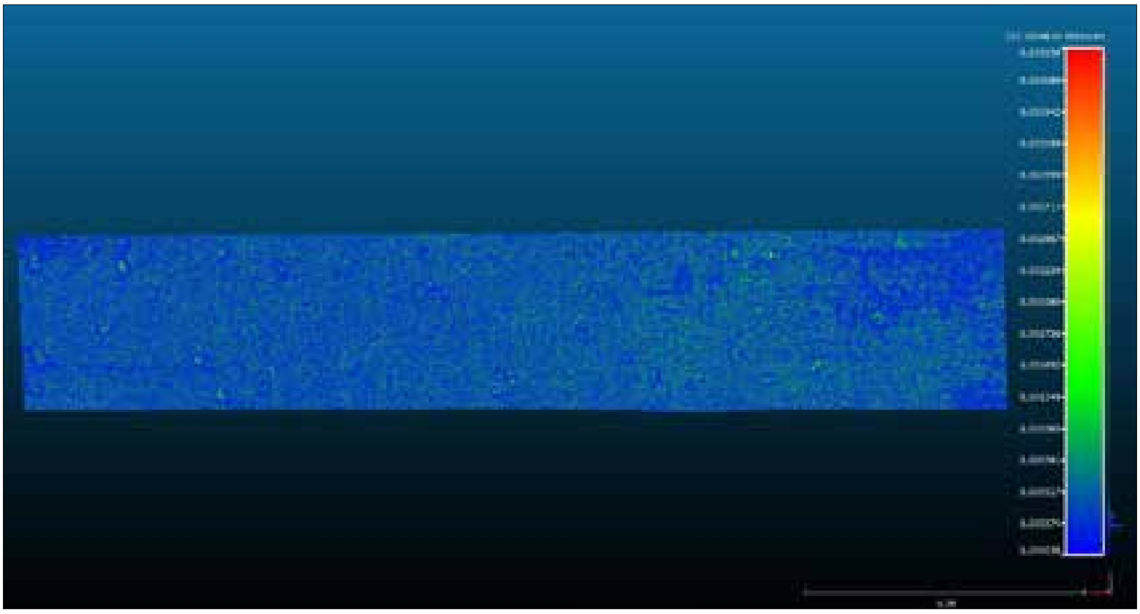

Figure 15: Scalar field of 1.6mm resolution, normal sensitivity laser scan point cloud, using the high sensitivity scan as reference. There is very little deviation between the two datasets.

Medieval door: Point cloud from still photography x point cloud from video stills SFM photogrammetry

Scalar fields were created to compare the deviation between the point clouds produced from SFM photogrammetry using video stills and still DSLR photography of a single horizontal panel of the medieval door (figure 16). The comparison shows that the across the surface of the panel, in general the distance between the two point clouds most frequently falls between 0.007mm and 2.459mm, however in a few areas, there are larger distances of up to 5-6mm deviation between the datasets, when the histogram is observed.

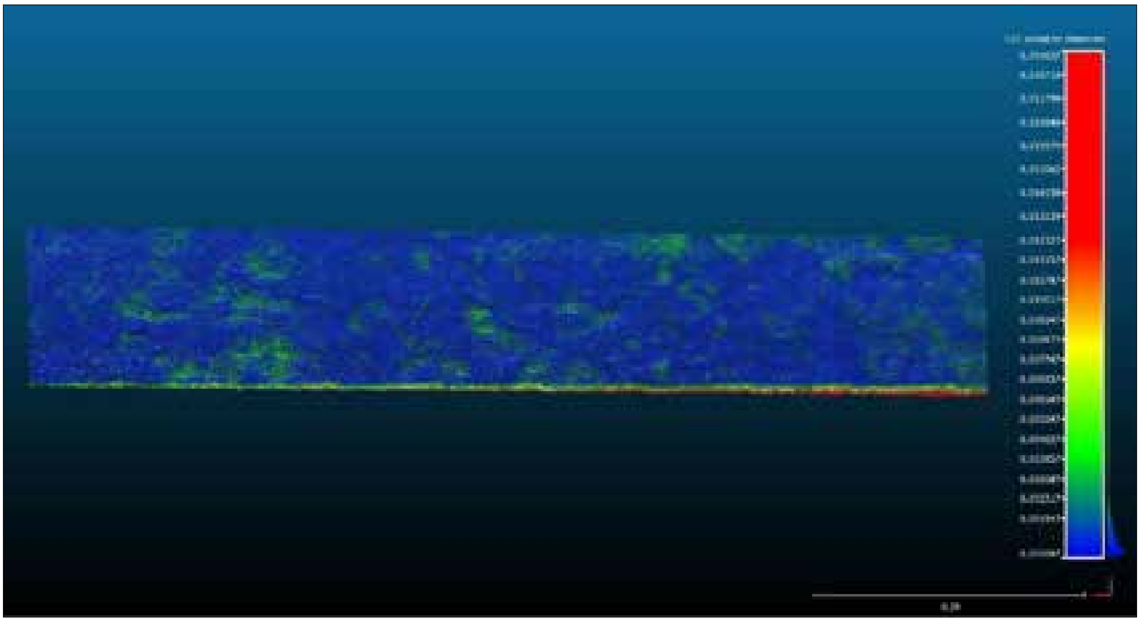

Figure 16: SFM point cloud from video footage, with scalar field mapped. Here, any area featuring red indicates where a deviation of over 10mm occurs between the video and still photography point clouds. The majority of the deviation is less than 1.5mm, but some areas deviate by 5mm (indicated as green).

The bottom horizontal line of points across the wooden panel, coloured yellow and red in figure 14, was discounted as these points did not feature in the still photography SFM point cloud, due to the two point clouds being manually cropped separately, which explains the high deviation displayed for these points.

Upon creating meshes from the point clouds, it is clear that these areas of the greatest distance appear across the surface of the wood as uneven indentations in the point cloud produced from video stills, whereas in the point cloud created from still DSLR photography, it appears that the surface of the door is smoother, and the carved details are better defined (figure 17).

Medieval door: Point cloud from still photography SFM x point cloud from 1.6mm normal sensitivity laser scan

It is evident from the above comparisons, that the laser scans had substantially less deviation between each dataset than that of the SFM using still photography and video footage. It has been discussed above that the video stills were of poor quality, and the greater distance of its point cloud from the one generated using still photography reflect this. For the purpose of recording medieval carvings in situ, it is clear still photography was more appropriate than the video set up used. However, it was considered beneficial to also investigate the difference between the still photography SFM and laser scan point clouds, as these produced more accurate datasets. It has been mentioned above that the coordinate data for SFM was taken from the laser scanner. As such, any deviation indicates a different alignment as calculated by Photoscan.

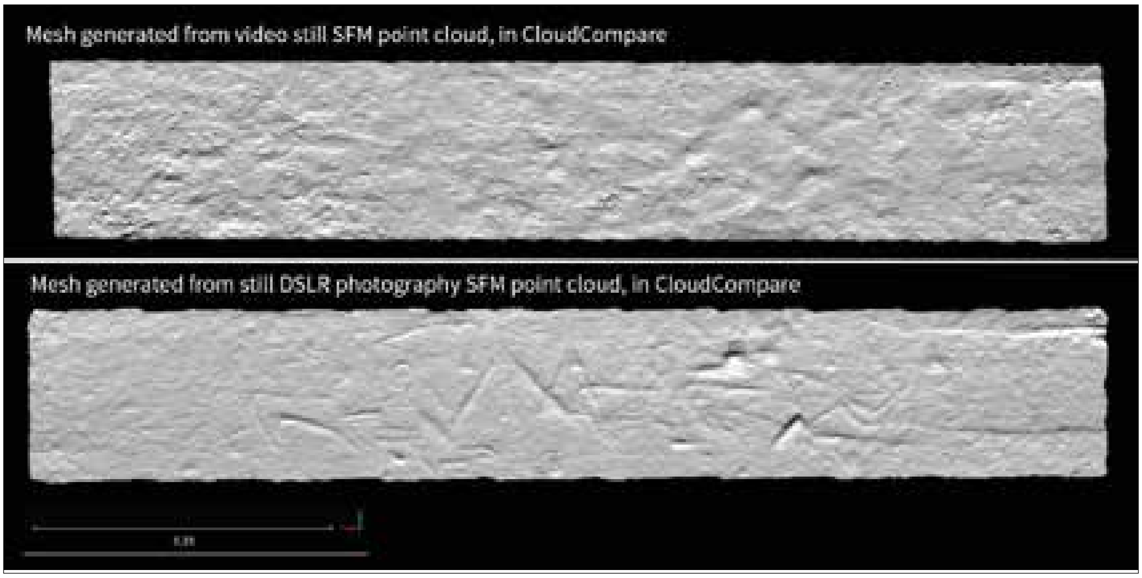

Figure 17: Meshes created from the SFM point cloud data in CloudCompare. Note how the video recording failed to capture any of the carved details on the door. In place of the carved details are areas of depression on the mesh surface. The still photography SFM mesh successfully depicts the carvings.

Observing the scalar field generated, it can be seen that most deviations are below 2mm, however there are areas where it increases to over 3mm (depicted in red on figure 18). Studying these areas, it is clear that these areas are where deep indentations, holes and cracks feature on the surface of the wooden panel. Without adequate coverage of such areas using either SFM photogrammetry or laser scanning, the quality and quantity of points can be poor and less accurate, as all edges of such deep marks were not recorded. It is highly likely that this was the cause of the high deviation in values for these areas. Despite this, the average difference of 2mm between the two point clouds is relatively small.

3D POINT CLOUD COMPARISONS – PRISONERS' CARVINGS

A section of the Prisoners' Carvings was extracted from point clouds produced from laser scans and SFM photogrammetry for analysis. Unlike the laser scans taken of the medieval door, all scans that recorded the Prisoners' Carvings used the same resolution (1.6mm). Additionally, scans were taken from different positions around Room 22, and at different heights, to collect as much data as possible, as some carvings are substantially deep in relief. The laser scan point clouds taken from the most oblique and distant scan position was compared to the one acquired from the closest and most parallel scan to the carvings, to determine the variation in their points and how much data may be lost from oblique scans. Additionally, the oblique scan point cloud was compared to the dense point cloud created using SFM photogrammetry, to further note any variations. Lastly, all five registered laser scan point clouds taken of the Prisoners' Carvings panel were merged together, to compare the point distances to the dense point cloud created using SFM photogrammetry.

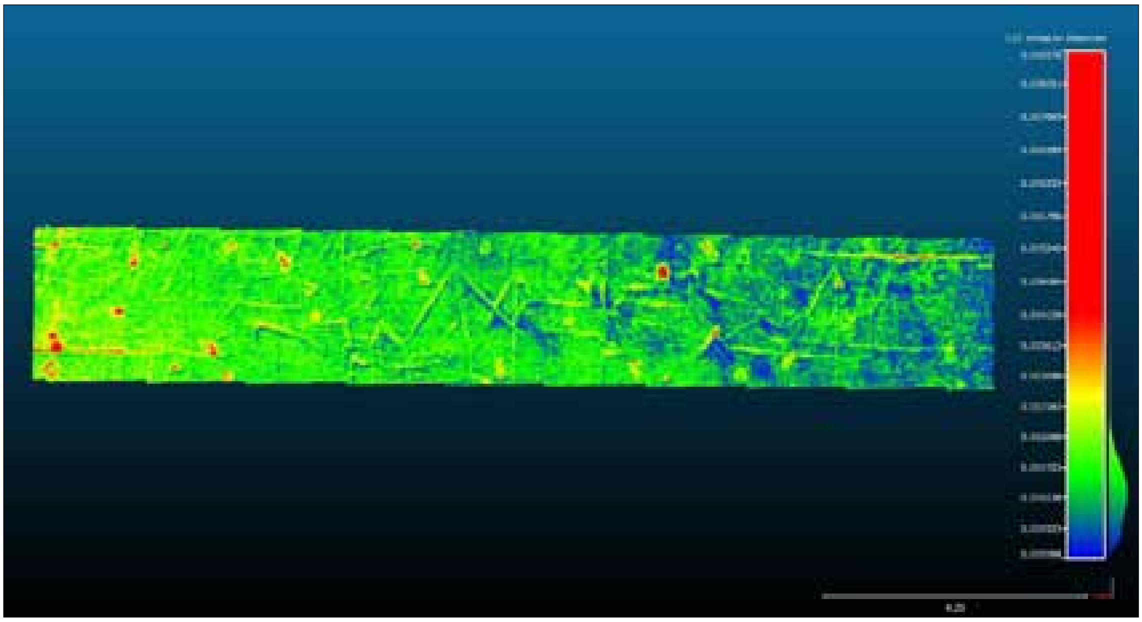

Figure 18: Point cloud from SFM photogrammetry, with scalar field mapped of distances between this and the laser scan point cloud.

Prisoners' Carvings: Point cloud from still photography x point cloud from video stills SFM photogrammetry

Scalar fields were created to compare the deviation between the point clouds produced from SFM photogrammetry using video stills and still DSLR photography of an area on the northwest facing wall of the Prisoners' Carvings room (figures 19 and 20). The comparison shows that there is a substantial amount of deviation between the two point clouds, as the scalar fields indicate that the majority of points between the two datasets are 2-4mm apart (see table 2). Considering a 3mm error is the maximum permitted under the metric survey specifications set by Historic England, such variance between the SFM photogrammetry from video and DSLR photography indicate they are not compatible, and should not be used together.

The poor quality of the mesh produced from the video footage, in addition to the misalignment error that was caused due to a lack of overlapping footage of some areas of the carvings, highlights that this particular video set up is not suitable for the acquisition of detailed 3D data of the Prisoners' Carvings. In contrast, the results produced from still photography were within the levels of accuracy required, with errors under 3mm using the laser scan coordinates as tie points for alignment, and the mesh produced from the point cloud successfully recorded the carved details.

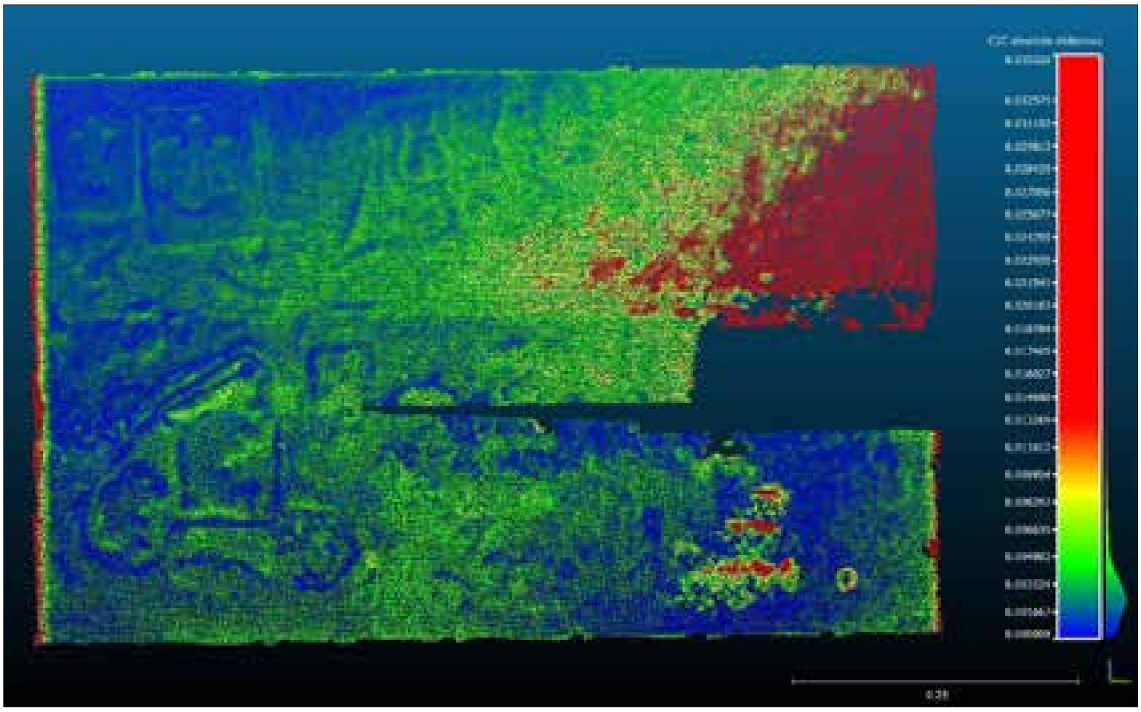

Figure 19: Scalar field of the point cloud produced by SFM from video footage, using the point cloud from still photography as reference. Red areas indicate a deviance of over 10mm. Note how the areas that are not misaligned, on the left, have less distance between the datasets.

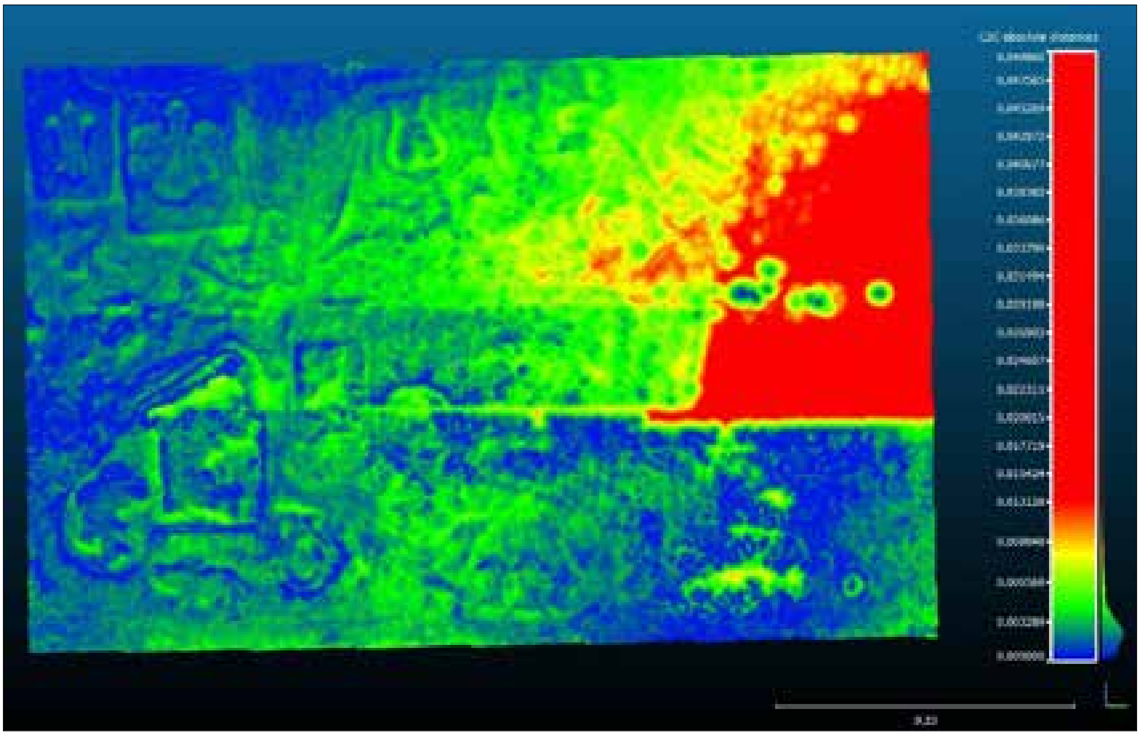

Figure 20: Scalar field of the point cloud produced by SFM from still DSLR photography, using the point cloud from video footage as reference. Red areas indicate a deviance of over 10mm. The two scalar fields both show the same deviations, particularly in the area where the video footage was misaligned due to lack of data, on the top right.

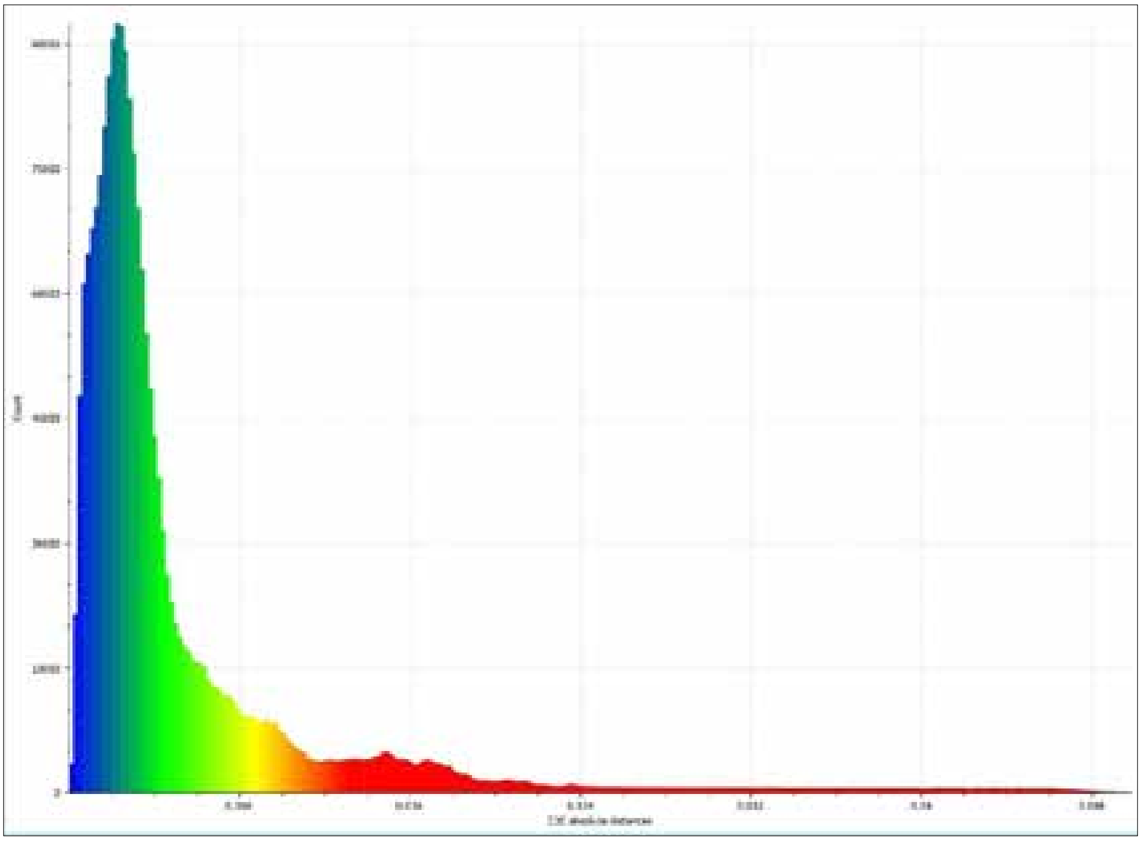

Table 2: The distance between points (x axis) and the number of points in the point cloud created from still DSLR photography SFM (y axis), using the point cloud from video footage as reference. The majority of points deviate by 0-8mm, however, more than 5000 points exceed a distance of 10mm.

Prisoners' Carvings: Point cloud from still photography SFM x point cloud from five merged 1.6mm normal sensitivity laser scans

Figure 21 shows the scalar field, and barring the vertical red line on the right side, which is an area that was cropped out of the laser scan point cloud, there is very little deviation between the two point clouds. The mean distance between them was 0.41mm and both datasets present the carvings very similarly, even considering how some of the carvings are carved deeply into the sandstone. It is possible that this was helped by the fact that there are no deep holes or cracks in the carved stone, unlike with the wooden door panel.

Additionally, these results highlight how the unreflective and mixed-colours of the sandstone walls are highly suitable for both SFM photogrammetry and laser scanning. In contrast, the dark polished wood of the medieval door is both monochrome and reflective; two properties that are known to produce poor SFM results (Schaich 2013, Nicolai et al 2014). Shiny surfaces are also difficult to record using laser scanners, and reflection of the laser from the object surface to the receiving unit of a ranging scanner is weak from dark coloured surfaces (Boehler and Marbs 2003, 699). As such, it is likely that these textural properties had more of an adverse effect on the data acquisition from the medieval door. Yet, as the comparisons in CloudCompare have shown, detailed point clouds of the door were still acquired using both techniques.

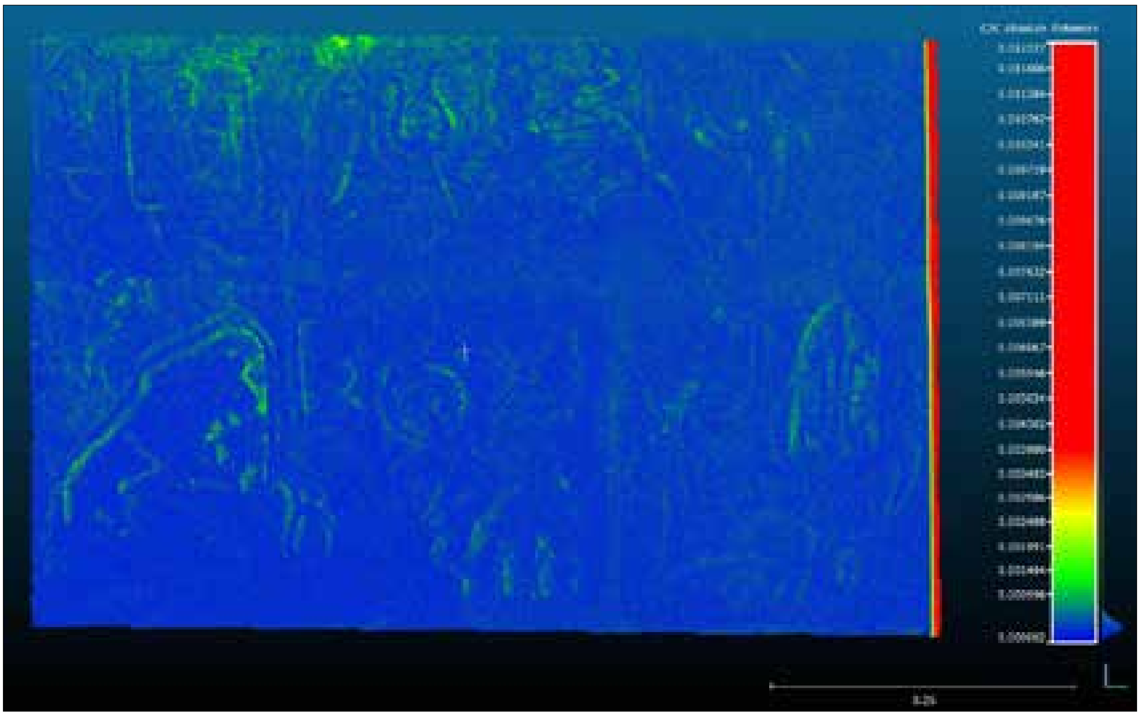

Figure 21: Scalar field of SFM point cloud from still photography compared to laser scan point cloud as reference. Red areas signify a distance of over 3mm.

Prisoners' Carvings: Point cloud from 1.6mm normal sensitivity laser scans - most oblique and distant x closest and parallel to carvings

The cloud to cloud distance was computed using CloudCompare and a scalar field produced to highlight the range of distances between the two. The mean distance between the point clouds is 0.0482mm and the standard deviation is 0.314mm. Considering this data alone, it appears that the variations are quite small. Additionally, the histogram indicates that all points fell into a distance of 2mm or less (table 3).

However, when the colourised scalar field is viewed, it is clear that the oblique angle and further distance of one scan shows significantly fewer points than the one taken from closer range, facing the carvings directly (figure 22). Figure 22 also clearly shows how the oblique angle of the scan has resulted in certain areas not being recorded, depicted in red. Additionally, due to the sharp angle of the scanner when facing the surface of the carvings, the more distant parts of the carved area have a sparser number of points. Figure 22 illustrates this clearly, as the more accurate and less deviant points (depicted as blue), slowly become more distant from the points of the closer laser scan point cloud, as deviation increases (as the colour changes to green).

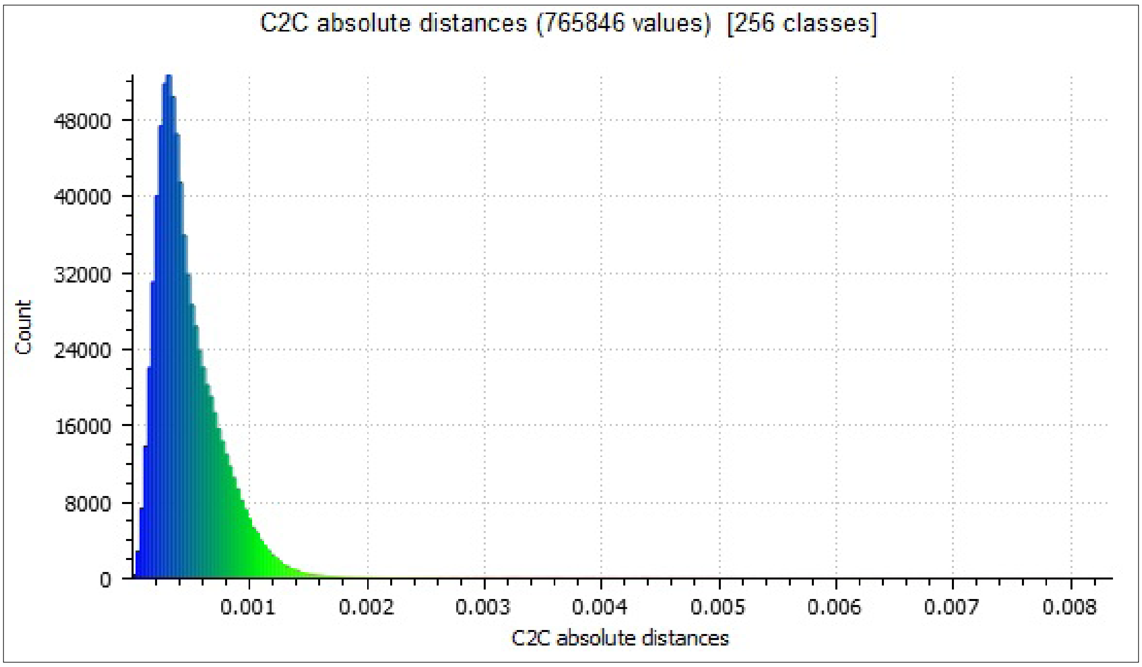

Table 3: Histogram depicting the scalar field showing the difference between the two point clouds

Figure 22: Scalar field of the oblique and further laser scan compared to the nearer scan, used as reference. Note the areas with fewer points in the oblique scan, coloured orange and red, to the bottom left corner of the image.

Prisoners' Carvings: Point cloud from 1.6mm normal sensitivity laser scan, most oblique and distant x point cloud from still photography SFM

The mean distance between the two point clouds is 1.548mm and standard deviation is 4.636mm. These distances are notably higher than those found from comparing the oblique laser scan point cloud to the one acquired from a closer range scan. Most points do not deviate beyond 1.8mm (table 4), however there are a few outliers.

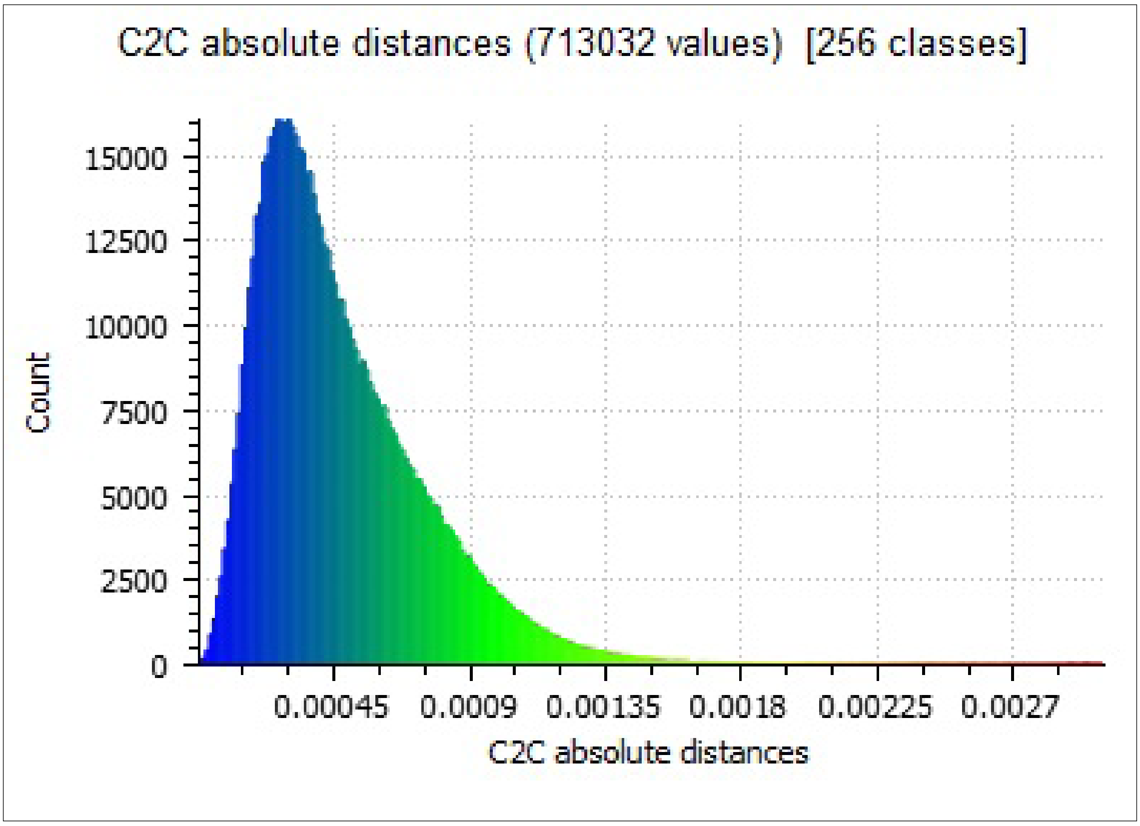

Table 4: Histogram showing the cloud to cloud distance variations up to 3mm between the oblique laser scan and SFM point clouds. Distances beyond 3mm are not shown, however there are very few points which vary to this extent.

The scalar field presented does not reflect the results shown from the cloud to cloud comparison of the close range and oblique laser scans seen in figure 23. Interestingly, the greatest deviations between this and the SFM photogrammetry dense point cloud are in the top left and bottom right corners, coloured green. This was unexpected, as it was predicted that the point distance would increase horizontally towards the right due to the angle of the scan, as the above comparison denoted (figure 23). Whilst this was not the case across the entirety of the laser scan point cloud, an identical area of fewer points can be recognised from this effect, to the left side of the border surrounding the smaller dolphin, coloured orange in figure 22.

Certain details, such as the crowned lion *passant guardant*, edges of the larger dolphin and its surrounding border also appear to be deviate more than shallower carvings, like the central rose badge and armed figure in the top right corner (figure 23).

Figure 23: Scalar field of the oblique laser scan point cloud compared to SFM photogrammetric point cloud. Note that the scalar field shows only the distances between points ranging from 0-3mm. All higher deviations were omitted in the colour scale to allow the distances within the Historic England Metric Survey guidelines to be focussed on in the analysis.

To summarise, it is clear that laser scans taken only from oblique angles do not provide sufficient coverage of an area to be recorded. The sharper the angle of the scan taken across a targeted surface leads to a more substantial reduction in the accuracy of the point measurements. Additionally, just as sufficient photographic coverage of a targeted object is needed for successful SFM photogrammetric processing, laser scan points can only be acquired of areas where the scanner laser beam can reach those surfaces. Positioned at an oblique angle, the carvings are less likely to be fully recorded, as areas in deep relief may not face the scanner.

3D MESH ANALYSIS

In total, four meshes were exported for analysis. As the comparative study of the point clouds found that the datasets generated from SFM using video footage was of substantially lower resolution than the still photography SFM and laser scan point clouds, it was processed no further. It was found that meshing the separate point clouds of all areas of interest was very difficult due to the large size of the Prisoners' Carvings datasets. The meshes required adjustments and edits in order to make them usable. This was an issue, as the original intention was to minimise editing of the data sets after the dense point clouds were cleaned to make them comparable. A compromise was made in dividing the Prisoners' Carvings meshes into separate sections, which were processed in 3DS Max by Andy Crispe. These were then viewed as separate PTM models. The meshes of the door panel did not require separating for PTM generation.

Qualitative comparisons were made, taken from the laser scan point clouds and still photography SFM dense point clouds of two particular areas of carvings, as described above. This section will present and review the quality of these meshes in comparison with each other, to determine which appears to be the most detailed and accurate record of the carvings featured.

Panel of medieval wooden door

A panel featuring medieval carvings of a human figure, zoomorphic creatures and arrow symbols was selected for a study of the decoration on the door. The visual differences between the meshes were examined using PTM models generated from the laser scan and SFM meshes. These were virtually lit under different lighting conditions, to reveal the carved details. A visual analysis was undertaken to determine which mesh presented the carvings with greater clarity. Figures 24-31 show the SFM and laser scan meshes virtually lit from the same positions, and are all at the same scale.

Lighting above the panel

Figure 24: PTM of the laser scan mesh, virtual lighting positioned above the panel.

Figure 25: PTM of the still SFM mesh, virtual lighting positioned above the panel.

Lighting below the panel

Figure 26: PTM of the laser scan mesh, virtual lighting positioned below the panel.

Figure 27: PTM of the still SFM mesh, virtual lighting positioned below the panel.

Lighting to left of panel

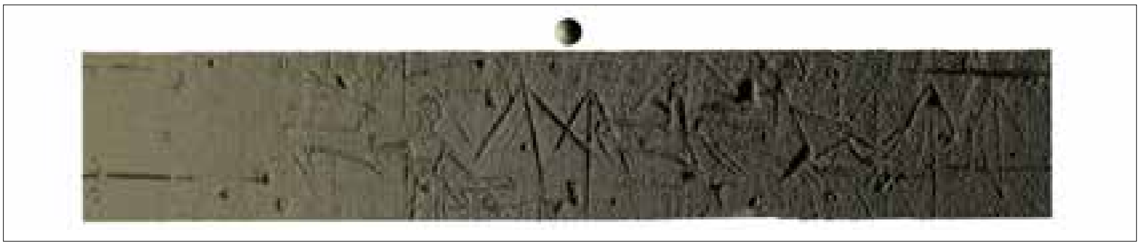

Figure 28: PTM of the laser scan mesh, virtual lighting positioned left of the panel.

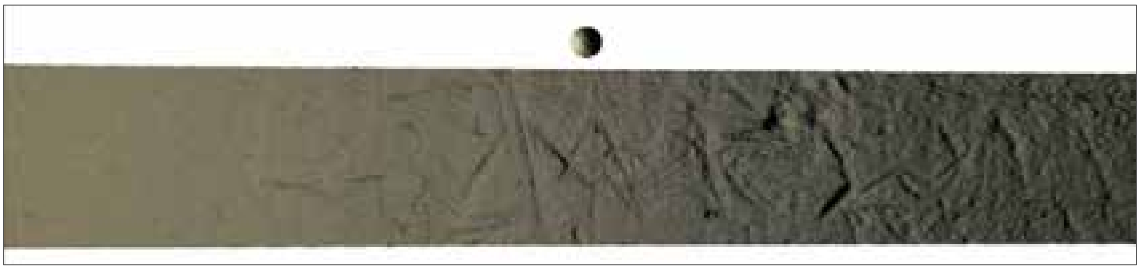

Figure 29: PTM of the still SFM mesh, virtual lighting positioned left of the panel.

Lighting to right of panel

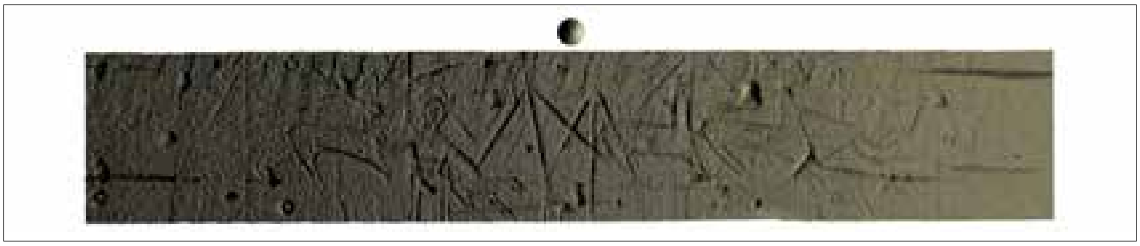

Figure 30: PTM of the laser scan mesh, virtual lighting positioned right of the panel.

Figure 31: PTM of the still SFM mesh, virtual lighting positioned right of the panel.

Comparing the two PTMs, it is clear that the one produced from the laser scan mesh shows the relief and depth of the carvings more clearly than the SFM mesh PTM. Details are brought out more sharply, in particular the carvings closer to the edges of the oak panel, such as the deer on the left, whose antlers are difficult to identify from the SFM mesh.

The SFM mesh appears to have a smoother texture that makes the carvings more difficult to distinguish, although the grainy appearance of the laser scan mesh does not realistically reproduce the true texture of the wooden surface of the door. Whilst the SFM texture appears smoother, neither mesh truly reconstructs the real surface of the door accurately (see figure 10 for photograph of the door). However, in this instance, the laser scan mesh does highlight the carvings in clearer detail when PTM is applied. The laser scan mesh has also recorded many iron nails that hold the panel to the rest of the door. These indentations are barely visible on the SFM mesh.

The resulting meshes have shown that SFM has struggled to recreate the sharp detail of the relief carvings, and the depth of these appears far shallower than the laser scan mesh. It has been mentioned above that dark and shiny, reflective textures are problematic for point alignment in SFM photogrammetry, and it is suggested these attributes have reduced the clarity of the carved details in the resulting mesh. Although reflective surfaces are also known to be problematic for laser scanning, in this case, the mesh produced from the scan point cloud does not appear to be adversely affected by this.

Visible and identifiable carvings on the door panel

Figure 32 depicts the author's interpretations of the carvings visible on one panel of the wooden door. Blue lines indicate animals, green for lines and arrows. On examination of the arrows, it appears that they are carved over the two deer-like animals on the right side, however the head of the middle deer is unclear. A possible depiction of a sailing boat was also identified, highlighted in orange (see figure 29 for shaded PTM).

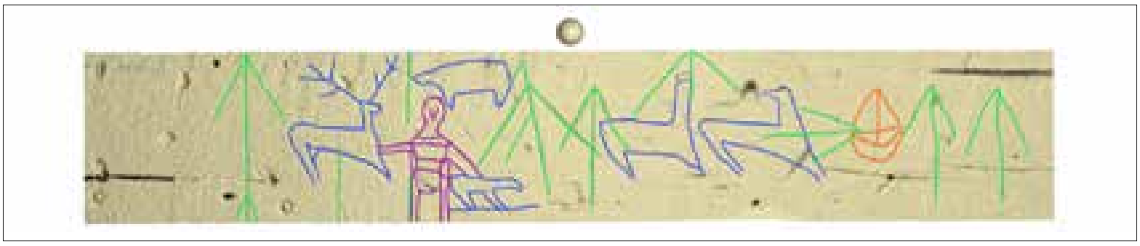

Figure 32: Interpretation of the different carvings on the door panel, using PTM images to examine the details.

Wills suggests that all of the earlier carvings both on the door and within the Prisoners' Carvings room are part of one large, panoramic hunting scene dating to the 10th century (2015, 71). Such a theory is plausible, as the style of these earlier carvings on both the walls of the room and on the door are identical, in the way deer are depicted (for example, see bottom right corner of figure 24). Examining the carvings on this single panel, it is possible they are a collective group, as it could be suggested that a scene is being shown, of deer being pierced by arrows, whilst the human figure is handling what could be a dog in their left hand, whilst the vertical line running up against their right arm may suggest a spear, bow or other hunting weapon. The animal to the top of the person's head may be another hunting dog. However, if this interpretation is to be used, the carving of a ship is quite out of context. It could possibly be suggested that this is a later addition by another person, possibly manipulating an existing arrow carving by altering the arrowhead into a triangular sail. The similarity of the ship to the arrows is such that Wills regarded it to be an arrow in his interpretation (2015, 145).

To better understand the designs of the Prisoners' Carvings, a comprehensive analysis of their form is required, and the production of PTM images has demonstrated how useful a technique this can be in helping to identify previously unnoticed carvings, and is recommended in any future analysis of the Prisoners' Carvings.

COMPARING POINT CLOUDS TO MESHES

After the meshes were generated, these were compared alongside their raw point clouds, to determine how much manipulation had occurred in Geomagic for the meshes to be generated without holes or anomalies. To compare a mesh to a point cloud, CloudCompare samples points from the mesh vertices. The distance between these and the point cloud was calculated and reviewed.

Medieval door 1.6mm normal sensitivity laser scan point cloud x mesh

Comparing the laser scan point cloud of the medieval door with resolution set to 1.6mm to the mesh created from this dataset, it is clear that there are very few deviations between the two. The histogram displays the distances between points, and it shows that all points were within a distance of 2mm of each other, and the majority had even smaller deviations (Table 5). The mean distance between points was 0.024mm and the standard deviation was 0.470mm.

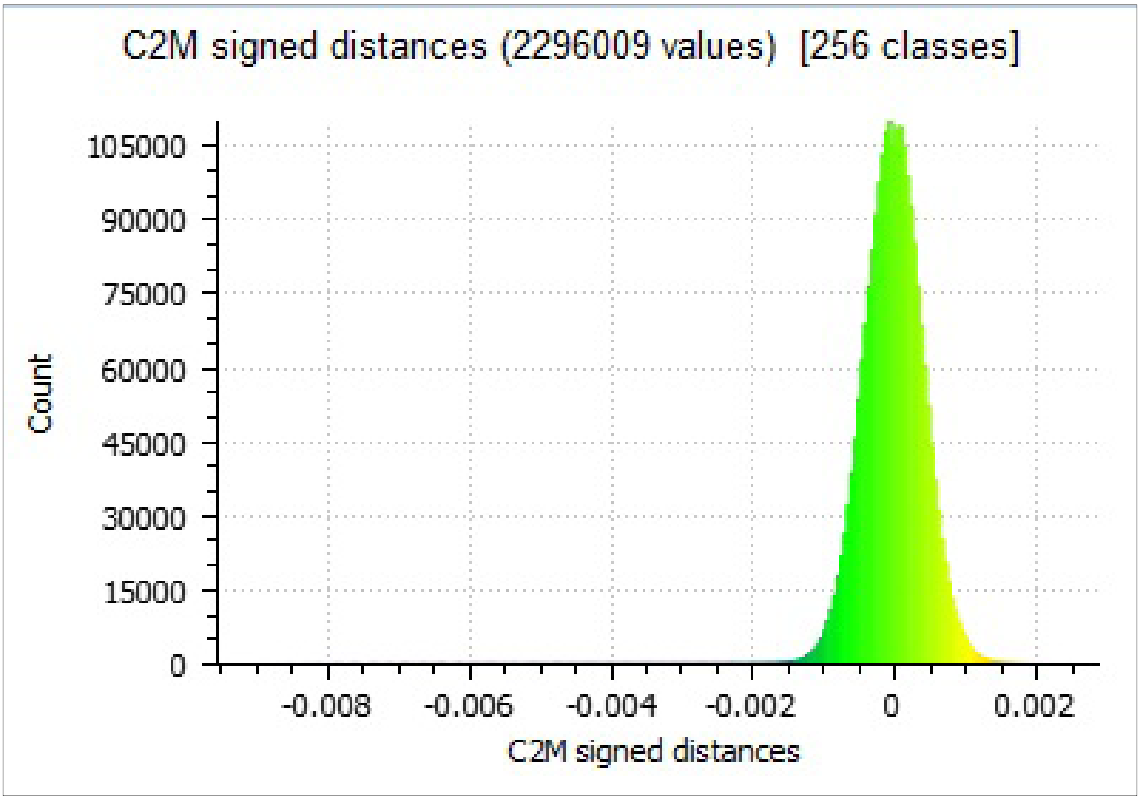

Table 5: Histogram of the computed distances between the point cloud and mesh vertices, processed using CloudCompare.

The scalar field generated comparing the point cloud to mesh displays these small differences clearly, across the surface of the door panel. The only area that depicts a higher deviation was the inwardly curved notch of the lower right end of the panel, that is coloured blue (figure 33). It has been discussed above that the data collected had insufficient coverage of holes and deep notches in the woodwork, with high deviations were found between the SFM and laser scan point clouds. This result reflects the same pattern.

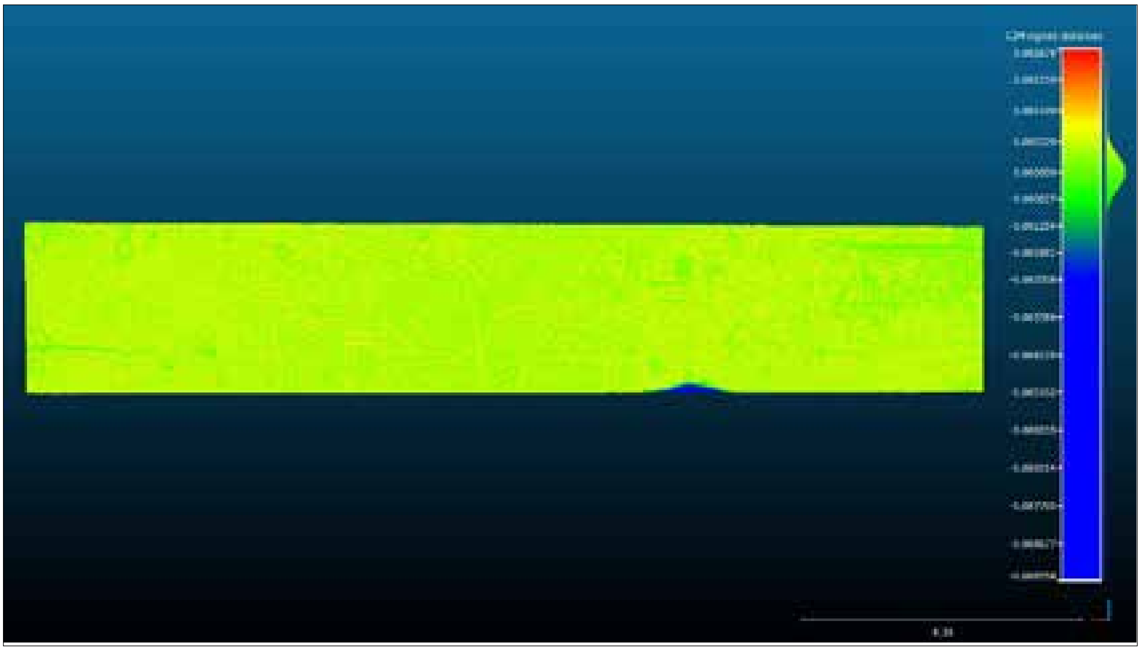

Figure 33: Scalar field showing the distances between points on the point cloud and mesh of the wooden panel from the medieval door.

Medieval door still photography SFM dense point cloud x mesh

The histogram displaying scalar field computed in CloudCompare shows that there is a deviation of less than 1.5mm for almost all points compared between the still photography SFM dense point cloud and its mesh (table 6). The mean distance between points was 0.014mm and the standard deviation was 1.085mm, showing that the difference in point distances between the SFM point cloud and mesh was even less than that of the laser scan.

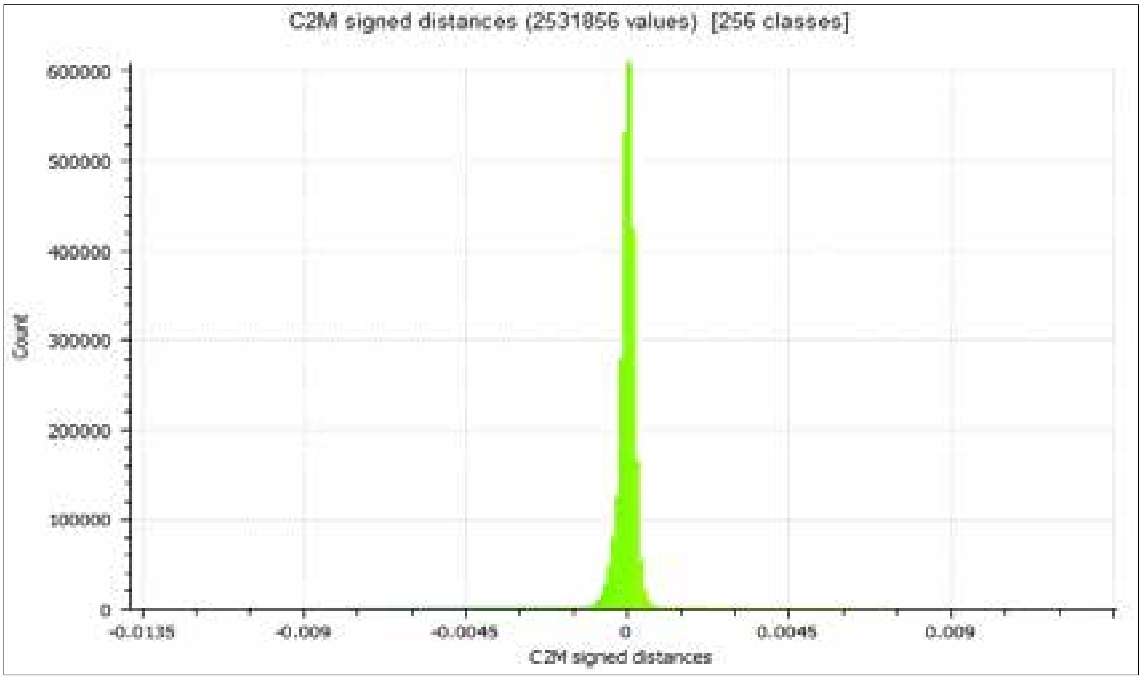

Table 6: Histogram of the SFM dense point cloud point distances computed against the mesh.

This is also clearly shown in the visual scalar field colourisation of the point cloud data, when compared to the mesh as a reference (figure 34). The bottom edges of the point cloud deviate from the mesh more, as they are coloured blue, yellow and orange. This is because they have been manually cropped, not exactly covering the same edge areas as the mesh.

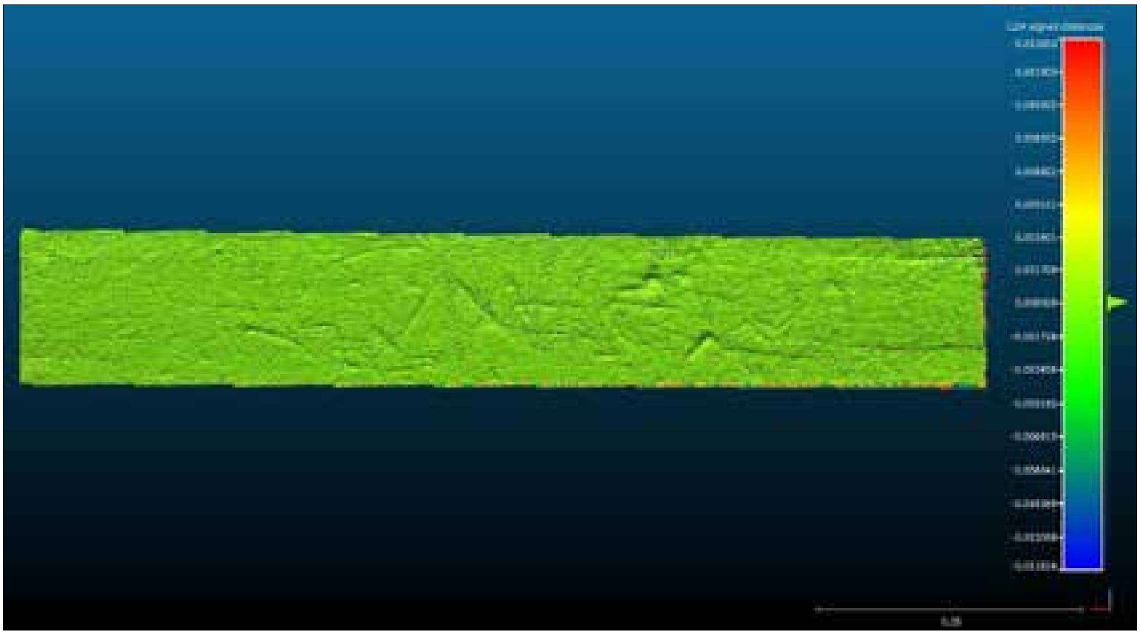

Figure 34: Scalar field showing the distances between points on the SFM dense point cloud compared to those of the mesh of the wooden panel from the medieval door.

Prisoners' Carvings 1.6mm normal sensitivity single close range laser scan (from oblique angle) point cloud x mesh

The mean distance between the point cloud points compared to the mesh was 0.0002mm and the standard deviation was 0.237mm. The deviation of all points was below 1mm.

Prisoners' Carvings 1.6mm normal sensitivity five merged laser scan point clouds x mesh

The mean distance between the point cloud points compared to the mesh was 0.033mm and the standard deviation was 0.834mm. The deviation of all points was below 1mm.

Prisoners' Carvings still photography SFM dense point cloud x mesh

Noticeably there was hardly any deviation between the point cloud and mesh. The mean distance was 0.025mm and the standard deviation was 0.902mm. The scalar field histogram shows how all distances were less than 1mm apart (table 7).

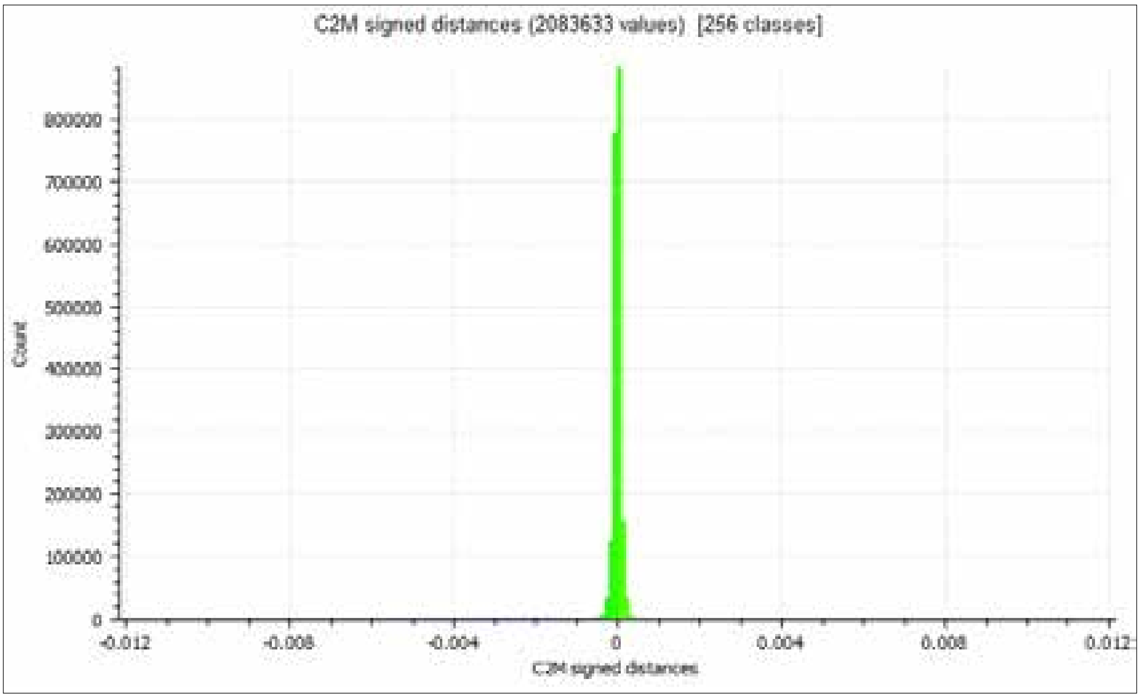

Table 7: Histogram showing the distance of the SFM point cloud of a section of Prisoners' Carvings compared to the mesh.

On the scalar field, areas around the edges coloured red or blue are areas which were cropped out of the mesh, so there was no data for the point cloud to be compared against (figure 35).

Figure 35: Scalar field of SFM point cloud distances computed against the mesh.

PART 4: DISCUSSION OF RESULTS AND CONCLUSION

POINT CLOUDS FROM DIFFERENT GEOSPATIAL IMAGING TECHNIQUES

For all laser scan point clouds, it was found that even with different resolution and sensitivity settings, the variation in distance between points was small, with all differences falling below 3mm. In contrast, the SFM point clouds produced more varied results, particularly for the Prisoners' Carvings point clouds, as the cloud computed using video still footage contained substantial amounts of distortion due to misalignment of points. Many of the video stills were out of focus, due to the lack of an autofocus video setting on the camera used. Additionally, there was a lack of overlap in the video still imagery, caused by the motion of the camera operator while filming took place. It is considerably more challenging to track the placement of the camera while it is in motion than when taking individual still shots from a tripod, and at the time of recording, we were unaware that the overlap was missing, that caused this problem. As imagery overlap and repeat coverage is crucial to correctly align imagery to be processed using SFM, it was not possible to fully rectify this problem during the processing stage. As a result, the video recording used for this project's test would not be recommended for future surveying of the carvings.

Comparing the differences between the still photography SFM and laser scan point clouds of the medieval door panel shows that the majority of the points are complementary, with deviations near 2mm being most frequent, however some significantly larger differences were present, where holes and deep marks in the wood were located. A lack of detailed coverage from either method meant that there were few adequately recorded points, and due to their scarcity, the variation between their locations between the laser scans and SFM was substantial. It is suggested that these clouds are comparable, but the variation of laser scan settings produced far smaller differences in distance.

It is unsurprising that there is little deviation between all of the compared laser scan point clouds, as the distance from the scanner to the recorded objects was very small. Whilst the settings used were either 1.6mm or 3.1mm, in reality the scanner was never further than 3 metres away from the objects.

The laser scans of the medieval door were taken at most from 1.7 metres away. As such, the true resolution of the point cloud with resolution set to 3.1mm was 0.53mm, whilst the 1.6mm resolution scans produced even denser point clouds with points 0.27mm apart. Similarly, the Prisoners' Carvings were at most 2.8m away from the scanner. Considering the resolution used was 1.6mm, in reality this would have been a minimum resolution of 0.45mm of the carvings. As such, all of the laser scan point clouds had sub-millimetre resolution.

DIFFERENCES BETWEEN POINT CLOUDS AND MESHES

Compared to the variance in distances between the different point cloud datasets, the analyses made of point cloud and their resultant meshes showed that although variance was produced from the process of meshing compared to the original point clouds, the differences between these were very small. This is unsurprising, as the meshes were directly derived from the point clouds.

The comparison has shown that the mesh vertices are not completely identical to the point clouds, demonstrating that in producing the meshes, subtle changes have taken place to construct a solid 3D surface from the dense point cloud.

VISUAL QUALITY VERSUS DATA ACCURACY

Overall, the results of the point cloud comparisons have shown that the variance between the SFM and laser scan datasets is relatively small and therefore quite accurate. Despite this, the PTM analysis of the 3D meshes of the wooden door have highlighted that visually, the results look very different. The PTM from the laser scans looked much sharper and carved details are easier to define, although the overall surface of the mesh has a pitted appearance. In contrast to this, the SFM mesh was smoother and as such reflects the surface of the wooden panel more accurately. Although this is the case, the mesh was also less well defined and certain details were difficult to discern.

CONCLUSION

As the aim of producing 3D records of the carvings was to produce a detailed record of their current appearance, and to help in identifying different carvings on these surfaces, it can be concluded that both SFM photogrammetry and laser scanning have met these objectives, albeit separately. For the purpose of being used as an aid to identify and distinguish different carvings, this study has shown that it is clear that meshes from laser scans have processed as PTM images better than SFM photogrammetry. Whilst this is the case, the laser scan point cloud did not process into a mesh that truly reflected the smooth texture of the wood that was scanned. It is possible that the dark, reflective nature of this material caused such problems for the laser scanner, although the scanner did successfully collect detailed point data on the depths of the carvings. Considering this, it can be suggested that further laser scans of dark, polished wooden artefacts be taken, processed and analysed, to determine if it is the reflective property or dark colouring of the material that caused the pitted effect in the mesh, or whether this was a processing issue.

The 3D mesh produced from SFM was less well defined than the laser scan mesh, and this was unexpected, as the close range and wide angle of the photographs taken should have allowed for sufficient overlap and detail of the carvings. However, uneven and varied lighting was an on-going problem for the photographic recording on site. Room 17, where the wooden door is displayed, is artificially lit by harsh strip lights mounted on the ceiling. As the recording took place during visiting hours, it was not possible to turn these lights off, and their direct reflection from the shiny dark surface of the door produced very unevenly lit images.

Additionally, natural light from a southeast direction shines through the room from a window, adding further unfavourable light. The same problems were met in Room 22, where the Prisoners' Carvings are situated. Again, due to the recording taking place during visiting hours, it was not possible to block light from the room's window, nor was it possible to turn off the artificial light. Small LED light panels were used to aid in lighting the carvings more evenly, however the complex arrangement of the carvings and the physical constraints of the small rooms made this very difficult. It can be suggested that for more evenly lit photographs which would produce improved SFM results, a repeat survey could take place, where the lighting is fully controlled by turning off and covering unwanted lights and more LED light panels to cover the carvings systematically.

This study has shown that with the Canon 5D MKII's video capabilities, using video still footage for SFM is not ideal, and although results are produced, they lack the accuracy, quality and control of the imagery produced from the still photographs. The laser scanner produced the most detailed record of the carvings, however the large file size of the 3D mesh outputs is problematic for PTM processing. In summary, it has been shown that both techniques are capable of producing detailed 3D model outputs, however improved photographic recording could produce better SFM results which may reflect that of the laser scanner even more closely.

In conclusion, it has been shown that generating PTM models from the meshes has been a very useful visual technique of revealing details of the carvings in more clarity, allowing for them to be studied remotely. It would be possible to conduct a detailed examination of the carvings using the 3D outputs generated in this survey, and such a study may aid in better understanding how and when the carvings were made. However, any future research or analysis must acknowledge that the comparisons between the point clouds taken from laser scanning and SFM have shown that the datasets have shown some slight variance, so in using both their measurements are not precise. This survey has shown that PTM is highly useful in helping to identify historic graffiti and carvings, and in examining just one wooden panel has helped to detect several carvings that have previously gone unnoticed. It is therefore highly recommended that a comprehensive archaeological survey of the Prisoners' Carvings should apply virtual lighting to 3D models, as an invaluable technique in studying the carvings' forms and history.

BIBLIOGRAPHY

Boehler, W. Bordas Vicent, M. and Marbs, A. 2003. 'Investigating laser scanner accuracy', in *Proceedings of CIPA XIXth International Symposium, Antalya, Turkey 30 Sept-4th Oct*, pp. 696-702

CloudCompare. 2015. *CloudCompare V.2.6.1 User Manual*. Available: http://www.cloudcompare.org/doc/qCC/CloudCompare%20v2.6.1%20-%20User%20manual.pdf. Last accessed 3rd Aug 2016

English Heritage. 2011. *Carlisle Castle – survey of carvings in keep – 11/113/5P – survey team*, ST010712/004/07, unpublished research project file

English Heritage. 2016. *Carlisle Castle*. Available: http://www.english-heritage.org.uk/visit/places/carlisle-castle/. Last accessed 13th Oct 2016

Field, F. J. 1937. 'The carvings in the entrance to Major Maclvor's cell, Carlisle Castle', *Transactions of the Cumberland Westmorland Antiquarian and Archaeological Society* 2 (37), pp.13-23

Leica Geosystems. 2015. *Cyclone pointcloud export format - Description of ASCII .ptx format*. Available: http://w3.leica-geosystems.com/kb/?guid=5532D590-114C-43CD-A55F-FE79E5937CB2. Last accessed 26th Jul 2016

Leica Geosystems. 2016. *Leica ScanStation P30/P40 Product Specifications*. Leica Geosystems, Heerbrugg

Nicolae, C., Nocerino, E., Menna, F. and Remondino, F. 2014. 'Photogrammetry applied to problematic artefacts', in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XL-5, pp. 451-456

Schaich, M. 2013. 'Combined 3D scanning and photogrammetry surveys with 3D database support for archaeology and cultural heritage. A practice report on ArcTron's information system aSPECT3D', in *Proceedings of Photogrammetric Week 2013*, pp. 233-246

Summerson, H. 2008. *English Heritage Guidebooks: Carlisle Castle*, English Heritage, London

Turk, G. 1994. *The PLY Polygon File Format*. Available: http://www.dcs.ed.ac.uk/teaching/cs4/www/graphics/Web/ply.html. Last accessed 26th Jul 2016

Wills, H. G. 2015. *The Best Kept Secrets of the Western Marches*, Arthur H. Stockwell, Devon

McCarthy, M.R., Summerson, H.R.T. and Annis, R.G., 1990. *Carlisle Castle: a survey and documentary history* (No. 18). Historic Buildings & Monuments Commission for England, London

APPENDIX 1: LEICA SCANSTATION P40 PRODUCT SPECIFICATIONS (FROM LEICA GEOSYSTEMS 2016)

System Accuracy	
Accuracy of single measurement *	
Range accuracy	1.2 mm + 10 ppm over full range
Angular accuracy	8" horizontal; 8" vertical
3D position accuracy	3 mm at 50 m; 6 mm at 100 m
Target acquisition **	2 mm standard deviation at 50 m
Dual-axis compensator	Liquid sensor with real-time onboard compensation, selectable on/off, resolution 1", dynamic range ±5', accuracy 1.5"

Distance Measurement System				
Type	Ultra-high speed time-of-flight enhanced by Waveform Digitising (WFD) technology			
Wavelength	1550 nm (invisible) / 658 nm (visible)			
Laser class	1 (in accordance with IEC 60825:2014)			
Beam divergence	< 0.23 mrad (FWHM, full angle)			
Beam diameter at front window	≤ 3.5 mm (FWHM)			
Range and reflectivity	Minimum range 0.4 m			
		Maximum range at reflectivity		
		120 m	180 m	270 m
	P30	18%	-	-
	P40	8%	18%	34%
Scan rate	Up to 1'000'000 points per second			
Range noise *	0.4 mm rms at 10 m 0.5 mm rms at 50 m			
Field-of-View				
Horizontal	360°			
Vertical	290°			
Data storage capacity	256 GB internal solid-state drive (SSD) or external USB device			
Communications/ Data transfer	Gigabit Ethernet, integrated Wireless LAN or USB 2.0 device			
Onboard display	Touchscreen control with stylus, full colour VGA graphic display (640 × 480 pixels)			
Laser plummet	Laser class 1 (IEC 60825:2014) Centring accuracy: 1.5 mm at 1.5 m Laser dot diameter: 2.5 mm at 1.5 m Selectable On/Off			

Imaging System	
Internal camera	
Resolution	4 megapixels per each 17° × 17° colour image; 700 megapixels for panoramic image
Pixel size	2.2 μm
Video	Streaming video with zoom; auto-adjusts to ambient lighting
White balancing	Sunny, cloudy, warm light, cold light, custom
HDR	Tonemapped / full range
External camera	Canon EOS 60D and 70D supported

Power	
Power supply	24 V DC, 100 – 240 V AC
Battery type	2× internal: Li-Ion; External: Li-Ion (connect via external port, simultaneous use, hot swappable)
Duration	Internal > 5.5 h (2 batteries) External > 7.5 h (room temp.)

Environmental	
Operating temperature	–20°C to +50°C / –4°F to 122°F
Storage temperature	–40°C to +70°C / –40°F to 158°F
Humidity	95%, non-condensing
Dust/Water	Solid particle/liquid ingress protection IP54 (IEC 60529)

Physical	
Scanner	
Dimensions (D × W × H)	238 mm × 358 mm × 395 mm / 9.4" × 14.1" × 15.6"
Weight	12.25 kg / 27.0 lbs, nominal (w/o batteries)
Battery (internal)	
Dimensions (D × W × H)	40 mm × 72 mm × 77 mm / 1.6" × 2.8" × 3.0"
Weight	0.4 kg / 0.9 lbs
Mounting	Upright or inverted

Control Options
Full colour touchscreen for onboard scan control.
Remote control: Leica CS10/CS15/CS20/CS35 controller or any other remote desktop capable device, including iPad, iPhone and other SmartPhones; external simulator.

Functionality	
Survey workflows and onboard registration	Quick orientation, Set azimuth, Known backsight, Resection (4 and 6 parameters), Traverse
Check & Adjust	Field procedure for checking of angular parameters, tilt compensator and range offset
Onboard target acquisition	Target selection from video or scan
Onboard user interface	Switchable from standard to advanced
One button scan control	Scanner operation with one button concept
Scan area definition	Scan area selection from video or scan; batch job scanning

Ordering Information
Contact your local Leica Geosystems representative or an authorised Leica Geosystems dealer.

All specifications are subject to change without notice.
All accuracy specifications are one sigma unless otherwise noted.
* At 78% albedo
** Algorithmic fit to planar HDS 4.5" B&W targets

Scanner: Laser class 1 in accordance with IEC 60825:2014.
Laser plummet: Laser class 1 in accordance with IEC 60825:2014.

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APPENDIX 2: IMPORTING LASER SCAN COORDINATES INTO AGISOFT PHOTOSCAN FOR POINT ALIGNMENT AND PROCESSING

Prisoners' Carvings southeast wall still photography SFM

Used 10 picked target points from laser scan data of the wall. Of these, the targets with the least errors were P1, P2 and P9. Using these targets alone, the total error was 1.5mm. All other targets had errors above the 3mm accuracy required by Historic England's metric survey specifications (Andrews, Bedford, Bryan 2015). When these were included, the total error was 11.6mm. As such, only the three targets fitting the specification were used.

Prisoners' Carvings southeast wall video stills SFM

Used 10 picked target points from laser scan data of the wall, identical to those used for the still photography of this wall. Using all targets, the total error was 8.8mm. To meet metric survey specifications, only those targets having an error of 3mm or lower were used. Only P10 fell into this criteria, however when this was combined with P6, with an error of 3.66mm, the total error was 3mm. To improve the alignment of the 3D data, it was considered important to incorporate more than one target, therefore P6 was also used.

Medieval door still photography SFM

Used 10 picked target points from laser scan data of the door. Using all of the targets, the overall error was 4.2mm. As such, only the targets having an error of 3mm or lower were used. These were M2, M3, M4, M7, M8, M10. This reduced the overall error to 2.2mm.

Medieval door video stills SFM

Used 8 picked target points from laser scan data from the same set as those used for the still photography of the door, however, it was not possible to locate two of the targets (M9 and M10) precisely, so these were not included. Using all of the targets, the overall error was 4.3mm. As such, only the targets having an error of 3mm or lower were used. These were M1, M2, M3, M4 and M8. This reduced the overall error to 2.1mm, within the accuracy necessary for Historic England's metric survey specifications.

APPENDIX 3: PHOTOSCAN PROCESSING SETTINGS FOR SFM PHOTOGRAMMETRY OF PHOTOS FROM STILL PHOTOGRAPHY AND VIDEO

Photo alignment

Accuracy: high

Pair pre-selection: generic

Key point limit: 40,000

Tie point limit: 1000

All anomalous points were deleted prior to creating the dense point cloud e.g. distant points through a window. The region was aligned and resized to accommodate the points in the correct positions (red pane being upright).

Build dense point cloud

Quality: high

Depth filtering: mild

All anomalous points and sections of the dense point cloud that were not required for analysis of the graffiti or which provided some spatial context (e.g. small section of the wall surroundings) were removed to reduce file size and processing time for the mesh.

Build mesh

Surface type: arbitrary

Source data: dense cloud

Face count: high

Interpolation: enabled/disabled

Point classes: all

In some cases, where holes were clearly visible in the physical structure of the surface, interpolation was disabled to prevent Photoscan from generating texture where none existed in reality e.g. of the panel on the gatehouse).

To remove erroneous, non-connected geometry, the gradual selection tool was used to find such features, to be removed.

Build texture

Mapping mode: generic

Blending mode: mosaic (default)

Texture size/count: 4096 x 1

Colour correction enabled.

All settings were left as standard defaults.

Where used on site, scales were added to each Photoscan project, in addition to markers used to pick out the physical targets placed on site, where overlap was required of different chunks.

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