Chapter 21. Generating 3D CAD models from laser scanning point cloud data to monitor and preserve heritage buildings

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Abstract

Condition monitoring of buildings can benefit from 3D laser scanning since the geometry of the building and some key features and components can be identified for the purpose of retrofitting, cataloguing, or fully or partially reconstructing the building. The 3D reconstruction of heritage buildings, sites, and artifacts should be accurately performed so that their current state of conservation is conveniently studied to support imminent or future conservation actions.

Point clouds, as the raw data from 3D laser scanning, enable a general visual representation but cannot distinguish between detailed components and sub-structures in a true 3D CAD model. Hence, to achieve a 3D CAD model from point clouds, manual or semi-automated techniques will be needed. This chapter discusses and evaluates point cloud-based modelling approaches that can be adopted in historic buildings and sites to construct their 3D CAD model with geometrical alterations, also known as an as-built 3D heritage model. To do this, a case study of a particular historic building called Ye Olde Trip to Jerusalem, in the city of Nottingham (the United Kingdom), is addressed, which is claimed to be the oldest pub in England (1189 AD).

Being a reliable source of geometrical data to constitute Historic Building Information Models (HBIM), as-built 3D heritage models should be considered a pre-requisite for non-destructive monitoring strategy to retrofit and maintain building components. Moreover, they are useful to produce immersive experiences to explore and disseminate heritage assets.

Keywords

Terrestrial laser scanning; Point cloud data; 3D modelling; as-built; model accuracy; Historic building information modelling; HBIM; Conservation status analysis; Heritage; Ye Olde Trip to Jerusalem

1. Introduction

Historic buildings and sites, archaeological ensembles, the ancient built environment, landscapes and natural monuments, and museum artifacts, among others. Numerous examples of heritage remain today and are unique and valuable to humanity [1], which led UNESCO's World Heritage Convention [2] to emphasise the need to protect these assets for future generations and to enhance communication with communities. In this respect, in addition to the implementation of the World Heritage Convention itself, it aims to achieve an increase in public awareness, involvement, and support. Concerning the protection of heritage, international agreements and conventions such as the Athens and Venice Charters in 1931 and 1964, respectively, [3,4] highlighted the importance of the continuous maintenance and conservation of the monuments. These conventions considered the possibility of using modern techniques and materials in the restoration, but it was the International Charter for the Conservation and Restoration of Monuments and Sites of 1964 (the Venice Charter) that established that restoration, conservation, and excavation works must include accurate documentation in the form of critical and analytical reports, drawings, and photographs. This reveals how works that contribute to the protection of heritage can benefit from technological development at different stages of the process. In this line, taking into consideration the widespread limited availability of heritage documentation [5], López et al. [6] explained that the creation of structured virtual models as part of the architectural heritage restoration process is an urgent need nowadays. The geometrical information obtained from 3D scanning technologies constitutes diverse accurate qualitative and quantitative data [7] to provide an insight into the real state of conservation and the behaviour of the assets in order to generate new knowledge to become part of their life cycle. Consequently, the implementation of advanced technologies in the field of heritage is a significant step forward for the conservation of this sort of asset [8].

Antón et al. [9] highlighted the need to model accurate geometries of heritage sites and assets to constitute Historic or Heritage Building Information Models (hereinafter, HBIM, the application of Building Information Modelling (BIM) technology to heritage) for their management, conservation, and dissemination. To do this, they proposed a three-stage semi-automatic workflow for Scan-to-BIM based on data from massive geometrical data capture techniques [10] such as

Terrestrial Laser Scanning (TLS) and Structured-Light Scanning (SLS); given that the Structure-from-Motion (SfM) photogrammetric technique allows for generating textured 3D meshes, this technology could also be used to produce the 3D objects. Using TLS and SLS data (point clouds and 3D meshes, respectively), the authors evaluated the accuracy of diverse 3D meshing tools applied to different geometrical complexities. Next to that process, they generated closed polysurfaces in the form of Non-Uniform algorithms Rational Basis-Splines (henceforth, NURBS) to constitute the 3D solids representative of the building components studied. The authors chose the Industry Foundation Classes (IFC) format to ensure interoperability between the 3D modelling software and the BIM platform to develop the HBIM project of the heritage building. As indicated by the authors, this information model enables virtual reality experiences for dissemination to the public.

Advancing on the previous workflow, Antón et al. [11] delved into the processes and accuracies to produce the so-called *as-built* or *as-is* models of an archaeological site so that accurate analysis could be carried out on its parts. For this purpose, these authors developed a semi-automatic script in a visual programming language (Rhinoceros Grasshopper [12]) to ease the modelling process and lay the basis for the subsequent analysis. Given the excessively simplified modelling approaches detected in the related scientific literature, that research publication was useful to justify the need to model the geometrical alterations of heritage assets so that accurate analysis leads to characterising their real conservation status. The analyses performed in that research were surface and structural geometrical analysis, as well as structural behaviour assessment, but may include others such as static and dynamic loading patterns, erosion, moisture, and ageing phenomena, among others. This reveals the relevance of deformation modelling from remote sensing data, that is to say, representing geometrical alterations, in the study of the real condition of heritage buildings and sites.

Banfi, Brumana, and Stanga [13] also used NURBS through different *generative* modelling procedures to create the HBIM of the Basilica of Sant’Ambrogio in Milan (Italy), in the words of these authors, one of the most important Lombard monuments. The HBIM created led to the visualisation of the heritage building using extended reality technologies in order to raise awareness of the site. Using laser scanning 3D point clouds as a geometrical data source, Rausch and Haas [14] automatically fitted the shape and orientation of BIM parametric objects, this time, in the construction sector. To do this, the authors carried out metaheuristic optimisation in parameterisation using the control point-based schema (NURBS) with higher accuracy at the cost of processing time and a higher sensitivity to missing data in the 3D point cloud.

Besides, thanks to artificial intelligence, unstructured 3D point clouds (remote sensing data) can be processed with a higher degree of automation nowadays, thus reducing bias or errors by the operator. However, this technology, particularly deep learning, still needs to be improved to deal with the processing of larger point cloud datasets and the detection of objects in them [15]. Thus, in spite of the efforts made by the scientific community to support the automation of the 3D modelling process from remote sensing point clouds, these raw data enable a general visual representation but cannot distinguish between detailed components and sub-structures in a true 3D CAD model of the heritage building. As a result, to achieve a 3D CAD model from point clouds, manual or semi-automated techniques will be needed.

Based on the above, this research discusses and evaluates point cloud-based modelling approaches that can be adopted to create a comprehensive 3D CAD model of a heritage building. To do this, this chapter addresses the case study of a particular historic building called *Ye Olde Trip to Jerusalem,* in the city of Nottingham (the United Kingdom), which is claimed to be the oldest pub in England (1189 AD). This heritage building is listed as Grade II by Historic England on the National Heritage List for England with the entry number 1271192, first listed on 11th August 1952 [16]. It is located at Trip To Jerusalem Public House, Castle Road, with National Grid Reference SK 57028 39435, in a natural sandstone promontory called Castle Rock, beneath Nottingham Castle, and next to the Museum of Nottingham Life. There are two main parts of this two-storey building over the ground level: four main bodies shape the exterior part at different heights; among others that are not open to the public, four chambers connected both to the rest of the building and to the outside are excavated in caves under Castle Rock. The basement also occupies part of the cave network in the area. As expected, this more than 800-year-old building presents important deformations as a result of the course of time on walls, ceilings, structure, and roof. Consequently, producing a 3D model of the building and its surroundings constitutes a major challenge when taking into account their geometrical alterations, which makes it necessary to resort to the aforementioned manual or semi-automated 3D modelling strategies so far.

The rest of this chapter is organised as follows: Sect. 2 describes the research methodology focusing on the geometrical data capture and digital reconstitution of the case study. Sect. 3 presents and discusses the results of each stage in the methodology, and deals with the validation of the 3D modelling approaches. Finally, the conclusions and future work are described in Sect. 4.

2. Methodology

2.1. Digitisation and point cloud processing

2.1.1. 3D laser scanning

The geometrical data capture of Ye Olde Trip to Jerusalem was performed using a tripod-mounted Leica Geosystems ScanStation P20 3D laser scanner [17]. The scanning resolution was set at 6 mm at 10 metres and HDR (High Dynamic Range) image capture with automatic exposure and white balance was activated to map RGB (red, green, and blue) photographs onto the point cloud data. No targets were placed during the 3D laser survey given the sufficient overlap between stations.

The digitisation consisted of a total of 32 stations, i.e., scan positions, conveniently arranged throughout the building to avoid occlusions of the laser beam due to obstacles between the surfaces and the TLS device sensor. 9 stations were set outside the building (three of them in the front and rear patios), whereas 23 were set inside. The first station (upper right corner in Fig. 1) was intended to record the promontory and surroundings of the building facing East rather than the geometry of the building itself.

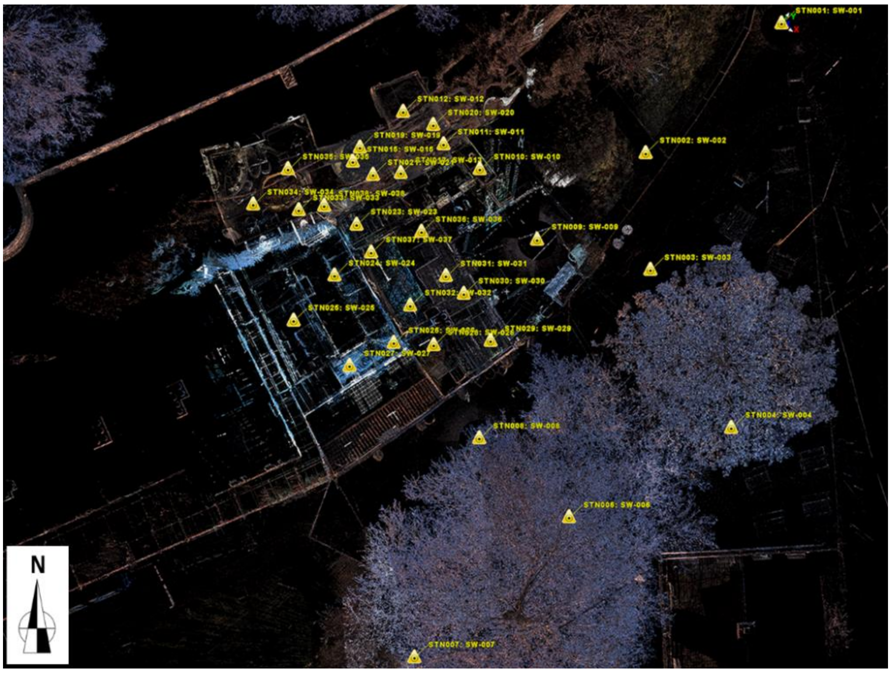

Fig. 1 – 3D laser scanning survey layout: Geo-referenced RGB point cloud data with stations and original axes.

2.1.2. 3D point cloud processing

Leica Geosystems Cyclone 9.4 software [18] was used to create the cloud constraints between the scan data of each station so that they were aligned in the same global coordinate system as in Fig. 1. This process, called *registration*, was performed automatically; no manual alignment was needed as expected from the scan overlap except for the attempt to improve *cloud constraint ID 51* between *station no. 10* and *station no. 28* because of the low overlap (overlap points) and greater distance between both stations. That manual alignment was conducted by selecting three pairs of common points between the two scans and was automatically refined in Cyclone through the optimisation tool. The registration diagnostics (cloud constraint alignment optimisation report), including the Root Mean Square Error (RMSE) of each constraint as per equation (1) [19], are shown in Table 1.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left\|p_i - q_j\right\|^2}, (1 \le j \le M), \tag{1}$$

where p_i and q_j are the nearest corresponding pair of points in clouds P and Q, respectively, and N and M represent the registration scales of those clouds. As indicated by the authors, a low value of RMSE reveals a better registration result, as expected.

Table 1 – 3D laser survey registration diagnostics.

Constraint ID	**Station no.**	**Station no.**	**Weight (coefficient)**	**Overlap (points)**	**Average error (m)**	**RMSE (m)**
7	34	35	0.7629	100,766	0.001	0.014
8	11	12	0.7107	57,733	0.001	0.012
10	33	35	0.7165	96,100	0.001	0.013
11	33	34	0.7082	100,866	0.001	0.012
13	15	21	0.6637	28,166	0.001	0.016
14	36	37	0.6563	46,566	0.000	0.014
15	11	13	0.5832	33,200	0.000	0.013
16	26	27	0.5821	48,333	0.001	0.016
17	28	29	0.5576	49,166	0.010	0.025
19	13	21	0.4718	28,466	0.000	0.013
20	30	31	0.4853	44,900	0.001	0.014
21	23	37	0.4491	37,500	0.001	0.014
22	24	25	0.4846	173,166	0.001	0.017
23	31	36	0.6168	48,166	0.000	0.017
24	29	30	0.4381	18,166	0.001	0.014
25	3	4	0.9676	794,700	0.001	0.019

26	32	37	0.5946	52,066	0.001	0.016
27	32	36	0.5720	44,133	0.001	0.015
28	2	3	0.9899	625,433	0.001	0.018
29	24	26	0.4161	108,733	0.002	0.018
31	13	15	0.3673	11,500	0.002	0.016
32	33	38	0.3718	52,266	0.000	0.012
33	6	8	0.6724	815,500	0.001	0.021
34	1	3	0.8395	679,900	0.001	0.018
35	10	11	0.3574	26,866	0.002	0.014
36	31	32	0.4433	47,833	0.002	0.018
37	3	6	0.6870	561,900	0.001	0.021
38	21	23	0.2914	24,333	0.001	0.017
39	34	38	0.3099	36,433	0.001	0.015
40	1	2	0.6964	641,700	0.002	0.018
41	2	4	0.5944	663,700	0.000	0.020
43	6	7	0.4388	506,833	0.001	0.021
44	2	6	0.4707	492,033	0.001	0.021
45	23	24	0.1798	47,400	0.001	0.012
46	35	38	0.1800	37,500	0.001	0.013
47	30	32	0.1778	27,100	0.002	0.016
50	12	13	0.1272	19,166	0.002	0.012
51	10	28	0.1069	8,233	0.021	0.019
52	3	9	0.1975	839,300	0.002	0.020
53	19	20	1.0000	44,100	0.001	0.012
54	20	35	1.0000	24,533	0.001	0.013
55	9	10	1.0000	73,900	0.001	0.015
56	8	29	1.0000	169,166	0.001	0.014
57	1	4	1.0000	669,700	0.001	0.018
58	7	8	1.0000	583,266	0.001	0.022
59	4	6	1.0000	849,833	0.002	0.021
60	4	8	1.0000	658,900	0.001	0.020
61	8	26	1.0000	43,900	0.001	0.016
62	13	23	1.0000	22,133	0.001	0.019
63	23	25	1.0000	40,733	0.002	0.015
64	25	26	1.0000	88,166	0.003	0.017
65	13	38	1.0000	16,966	0.000	0.016
66	21	38	1.0000	13,333	0.001	0.016

The presence of mobile furniture in the pub may have led to high RMSE values in some cases, given that tables and chairs did not remain in the same position at some point during the 3D survey. The registration yielded a mean absolute error of 0.002 metres (2 millimetres) for a total number of cloud constraints of 53. The number of cloud constraint IDs does not correspond to the total because the constraints of the stations discarded as erroneous for interruptions in the scanning were removed.

The registered point cloud was next segmented in order to remove existing noise and unwanted points and bodies in the scene. This was carried out by means of manual polygon fencing in the open-source CloudCompare [20] 3D point cloud processing software.

The following step was to geo-reference the global 3D point cloud so that the real location and orientation of the case study were determined in the 3D space. For this purpose, a GPS (Global Positioning System) survey was conducted using GNSS (Global Navigation Satellite System) technology based on Real Time Kinematics (RTK). The equipment in this research was a Leica GS18 receiver [21] and a Leica CS20 data logger [22], which captured the GPS data with an accuracy between 18 and 35 mm. 12 GPS points were recorded throughout the surroundings of the building with a '*GSxx*' ID, from *GS01* to *GS12*, with three recordings (three points) for each GPS position to minimise errors. The interpolated point coordinates for each group (points from *A* to *D*) and the reference point in the region are presented in Table 2:

Table 2 – Interpolated and reference recorded GNSS points.

Point ID	**X coordinate (m)**	**Y coordinate (m)**	**Z coordinate (m)**
A, near *station no. 1*: Mean(*GS01*,*GS02*,*GS03*)	457048.656	339457.809	30.316
B, near *station no. 1*: Mean(*GS04*,*GS05*,*GS06*)	457049.898	339451.764	29.661
C, near *station no. 4*: Mean(*GS07*,*GS08*,*GS09*)	457049.877	339431.323	28.426
D, near *station no. 9*: Mean(GS10,GS11,GS12)	457038.603	339442.478	29.404
RTCM-Ref 0130	462138.827	331671.348	74.660

The exact position of each GPS point on the site is shown in Fig. 2.

Fig. 2 – GPS recording at Ye Olde Trip to Jerusalem pub.

CloudCompare software was used to align the global 3D point cloud with the GPS cloud (the four interpolated GPS points in Table 2). This registration was performed by identifying each GPS point in the global point cloud; the programme computed the alignment from that point-pair picking process by considering the GPS cloud as the reference in the orientation.

Once the global point cloud was geo-referenced, it was subsampled (reduced in point number) to a resolution of 20 mm (minimum distance between points) in order to ease data processing and handling, and 3D visualisation; a lower file size implies using fewer computational resources. The reason for conducting subsampling after the geo-referencing process was that it is easier to identify the recorded GNSS points in the original point cloud than in a decimated dataset; after all, a reduction in the point count entails a loss in detail. Finally, further segmentation of the point cloud made it possible to subdivide the building and its surroundings into different parts to smooth the progress of 3D modelling.

2.2. As-built 3D modelling approaches

Once the geo-referenced point cloud was obtained, the next stage consisted in creating 3D objects to represent the geometrical alterations of the case study. This entailed undertaking manual and semi-automatic processes as explained in the Introduction. There are diverse modelling strategies such as the creation of transitions from point cloud sections or the contouring of point clouds to create planar surfaces to be later extruded into a 3D solid. However, given the comprehensive laser scanning survey of the case study, this research addressed two main approaches that will be validated in the next section: 1) the triangulation of point clouds, and 2) the generation of surfaces from those TLS data.

2.2.1. Point cloud discretisation: 3D meshing

Triangulation (discretisation) of the 3D point cloud geometry can be achieved using the Screened Poisson Surface Reconstruction algorithm [23]. CloudCompare software includes it as a plug-in. This algorithm allows for wrapping point cloud data with 3D meshes with lower or higher smoothening degrees once point normals have been calculated and the Octree Depth has been set [11]. The boundary method determines the creation (or not) of closed meshes for subsequent 3D solid modelling using NURBS. This modelling procedure was carried out for a cave sector in the largest room upstairs of the pub taking part of the main chimney shaft. For this purpose, the Octree Depth was set at level 10 given the considerable dimensions of the cave; otherwise, the 3D mesh would have a significant loss in detail. Fig. 3 displays both a part of the point cloud and the 3D mesh of the cave sector in solid and wireframe visualisation modes.

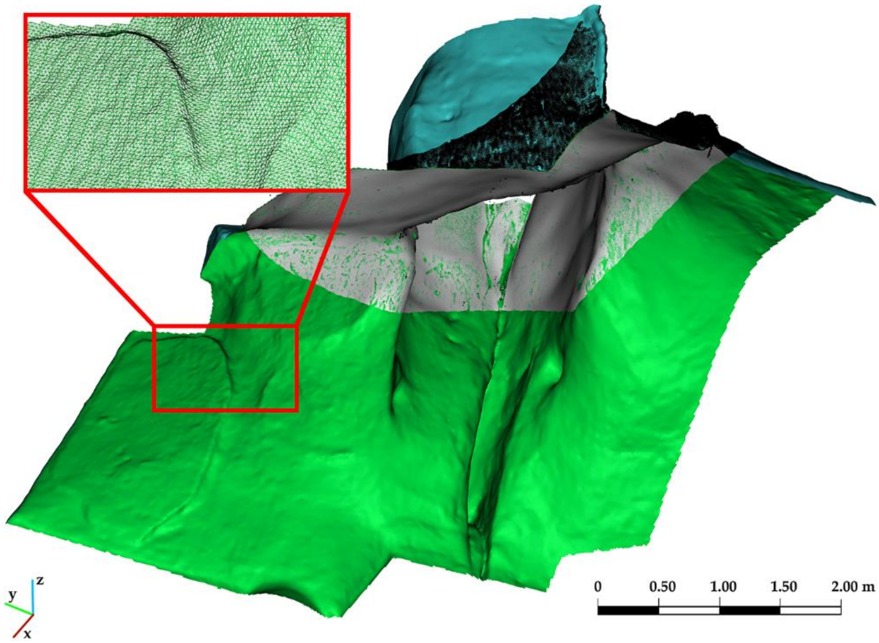

Fig. 3 – 3D mesh from point cloud: Upstairs room cave sector.

2.2.2. Patching point clouds with surfaces

This modelling approach automatically creates a surface that fits the geometrical alterations determined by the point cloud (Fig. 4). This is a means to reconstitute planar or quasi-planar elements such as warped walls and ceilings or irregular floors as those in Ye Olde Trip to Jerusalem. To do this, focusing on a sector of the corridor wall leading to the rear patio, the 'Patch' tool was used in Rhinoceros v7 [24] with 1 millimetre spacing between sampling points, 10 *U* surface segments and 10 *V* surface segments, with a rigidity degree equal to 1. These settings were used for sectors up to 3 x 3 metres in size. Sectors of different sizes were addressed using proportional settings. The surface excess can be removed by splitting in accordance with the point cloud or the component boundary.

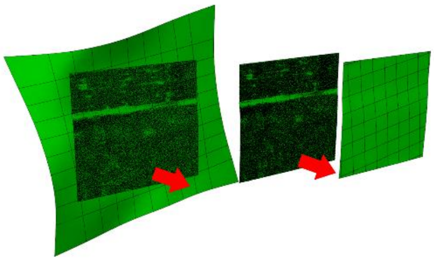

Fig. 4 – Patching point clouds using surfaces.

This non-planar surface modelling approach can be combined with the 'Create solid' (also known as *Sculpt* in other programmes) if a closed volume is created when shaping all wall faces, top, and bottom. 3D solids can be produced from this process as NURB objects (closed polysurfaces) to obtain independent entities that can be imported into a BIM programme. Their assembly and the integration of information from the heritage asset can constitute the HBIM project of the site.

3. Results and discussion

3.1. Point cloud data

With a view to presenting the result of the TLS survey, the global 3D point cloud of the case study is shown in Figs. 5 and 6 in the RGB visualisation mode and enhanced with intensities, respectively.

Fig. 5 – Ye Olde Trip to Jerusalem inn, Castle Rock, and Nottingham Castle: Geo-referenced RGB point cloud.

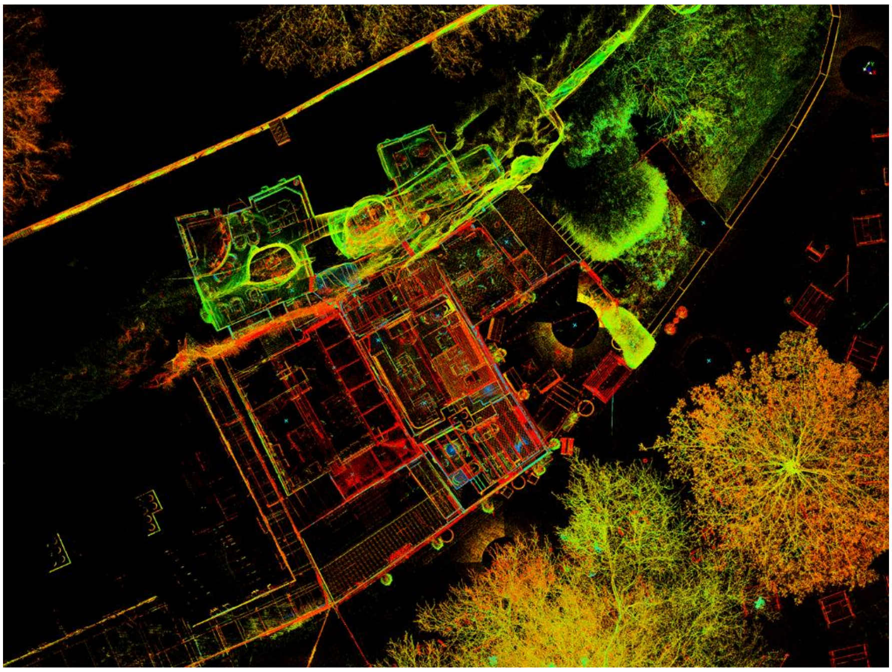

Fig. 6 – Layout of the Ye Olde Trip to Jerusalem inn: Geo-referenced point cloud enhanced with intensities. Orthogonal top view.

According to Antón et al. [7], point cloud intensities due to the reflection of the laser beam vary depending on the surface colour, material, texture, and humidity content. This can be seen in Fig. 6, where the red colour results from scanning the brilliant (reflective) black paint on wall skirtings, roof beams, and components of the timber structure. On the contrary, the green colour from scanning the stone surface of the caves accounts for a good (low) reflection (high intensity). Although low intensities entail greater laser beam uncertainty (thickness of the scanned surface in the point cloud), they still reveal the overall geometry of those elements, as Sect. 3.3.1. will demonstrate.

On the other hand, having an accurate TLS survey makes it possible to reveal spatial relationships between indoor and outdoor elements. This is the case of the two chimneys shaped inside the promontory that can be accessed from the main rooms upstairs and can be found thanks to their top end built in traditional red brick. In addition to the height and relative position of both the Castle wall and the building, Fig. 7 shows a section of the site and the actual correspondence between the chimney shafts and their top.

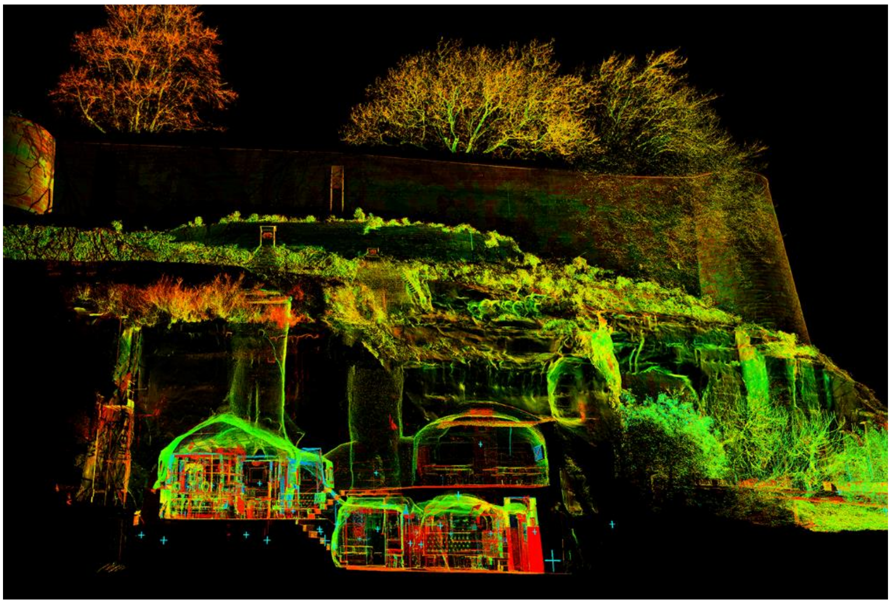

Fig. 7 – Interior of the Ye Olde Trip to Jerusalem inn and the natural sandstone promontory with the Castle wall: Geo-referenced point cloud enhanced with intensities. Section view.

3.2. As-built 3D model

The 3D modelling strategies described in Sect. 2.2 were adopted to complete the as-built 3D model of the Ye Olde Trip to Jerusalem case study and its surroundings. The model is displayed in Fig. 8.

Fig. 8 – Ye Olde Trip to Jerusalem inn and surroundings: Geo-referenced as-built 3D model.

In particular, the cave surfaces and the stones in the front patio were 3D semi-automatically reconstructed using meshes as in Fig. 3. Patching of point clouds using surfaces was implemented to produce warped walls and ceilings, as well as all roofs and floors at Ye Olde Trip to Jerusalem. Other modelling approaches adopted included the creation of closed polysurfaces from extruding planar surfaces from contours, combined with Boolean operations between the 3D solids. In addition, 3D primitives were fitted to the point cloud in orthogonal views to produce furniture and window parts. Besides, transitions ('Loft' tool in Rhinoceros) were created to 3D model the wine barrels at the front of the building. All 3D objects produced by following purely manual procedures were oriented using 3D rotation when they did not initially fit the point cloud data.

Speaking in qualitative terms, Fig. 8 reveals that there are elements in the scene that were less accurately modelled such as the furniture, the ground relief, and the Museum of Nottingham Life, among others. This is one of the limitations of this research, but it is justified because the focus was especially on the historic building as the most relevant asset of this heritage site. On the contrary, the 3D mesh that forms the natural sandstone promontory was created without having been able to remove the totality of the vegetation on it. Consequently, its geometry may vary from a 3D mesh produced from a hypothetical laser scan of the clean surface of the stone. However, as mentioned above, the focus of this research was on the deformations of the inn.

Finally, it is worth referring in this chapter to the computer used for 3D point cloud data processing and as-built 3D modelling of Ye Olde Trip to Jerusalem. It was a high-performance gaming laptop with an octa-core processor with hyper-threading at 2.30 GHz and a maximum turbo frequency of 4.60 GHz with 24 MB cache, 32 GB RAM DDR4 @ 3200 MHz, a 256-bit graphics card with 6144 cores @ 1245 to 1710 MHz and 8 GB GDDR6 dedicated memory @ 14 Gbps, and a 1TB NVMe PCIe Gen3x4 SSD (solid-state drive). From the experience of the authors, reaching a balance between the amount and density (file size) of the 3D data and the hardware specifications is essential to develop a 3D model of a complex case study with geometrical alterations, especially when financial resources are limited.

3.3. Validation

In order to validate the 3D scanning and modelling accuracies achieved in this research, it is worth quantitatively analysing: 1) the laser beam uncertainty and secondly, and 2) the point deviation against meshes and surfaces.

3.3.1. Low intensities in 3D point clouds

As seen above, low intensities in point clouds (red colour) imply a greater degree of laser beam uncertainty. However, the measured uncertainty value was 0.003 metres (3 millimetres) in those reflective areas such as black paint on wall skirtings against 0.001 metres (1 millimetre) in high-intensity data (green colour) as in the cave surface. This validates the use of the recorded low-intensity points to build the geometry of the case study.

3.3.2. 3D meshing and surface modelling

3D meshing (triangulation)

CloudCompare software was used to compute cloud-to-mesh distances so that the accuracy of the 3D meshing could be analysed. Fig. 9 shows the histogram generated for that purpose. Based on the cave sector presented in Sect. 2.2.1, the comparison between the point cloud and the 3D mesh also yielded the following accuracy indicators: Mean distance = 0.000001 metres; Standard deviation = 0.002312 metres. This reveals the great similarity between those 3D entities, thus validating the accuracy of the 3D meshing process to build the corresponding parts of Ye Olde Trip to Jerusalem.

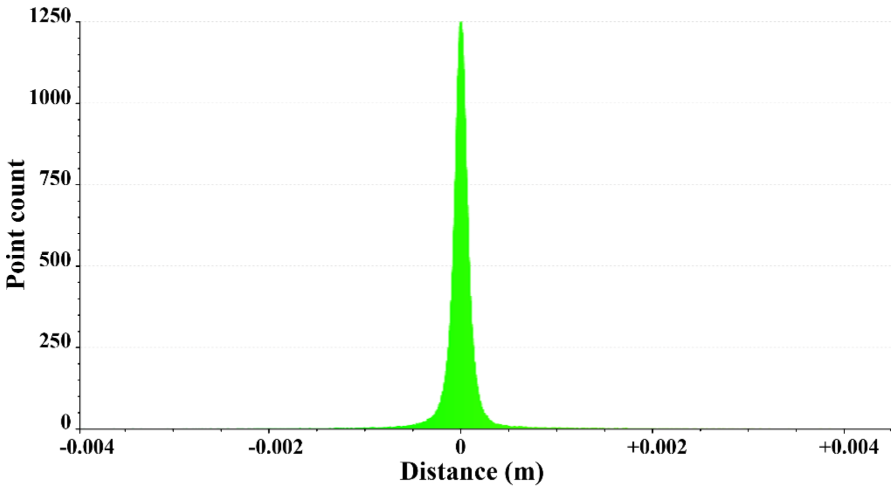

Fig. 9 – 3D meshing accuracy: Histogram of absolute distances between the sample cave 3D mesh and the original point cloud (metres).

Surface modelling

The sector of 1.75 m wide and 1.55 m high on the corridor wall leading to the rear patio was chosen for having low and high intensities in the point cloud. It is worth evaluating the accuracy of the surface sampling points against the original point cloud (6-millimetre resolution). The computed distances yielded the following quantitative data: Mean distance = 0.002558 metres; Standard deviation = 0.000972 metres. Fig. 10 illustrates the deviations between the surface produced and the point cloud data. Few are the points more than 4 mm distant from the cloud, which reveals decent geometrical preservation for a very low file size in the 3D model—a surface does not contain tens or hundreds of thousands of triangles (polygons) as in 3D meshes but only one per face. However, both the mean distances from the two modelling approaches and the comparison between Figs. 9 and 10 (with the same scale for clarity) reveal that the accuracy of the 3D meshing process is much higher than fitting non-planar surfaces. As a result, the cave surfaces present more detailed geometrical alterations.

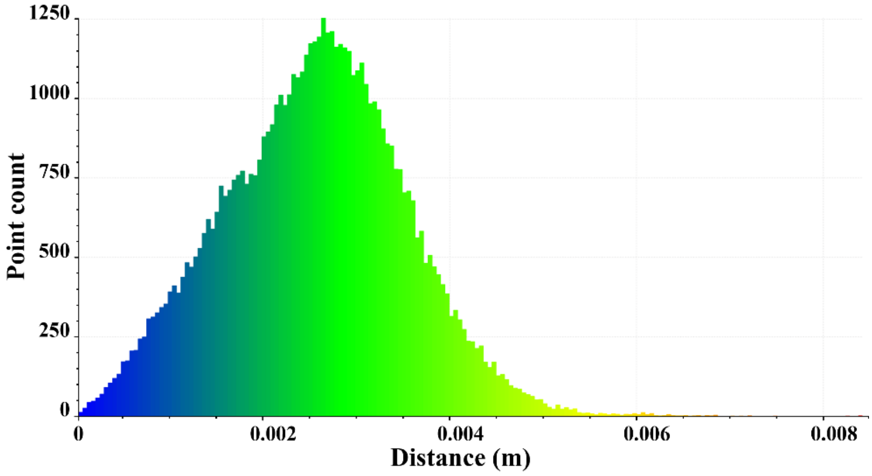

Fig. 10 – Surface modelling accuracy: Histogram of absolute distances between the sample surface geometry and the original point cloud (metres).

4. Conclusion and future work

The 3D reconstruction of heritage buildings, sites, and artifacts should be carried out on an accurate basis so that their current state of conservation is conveniently studied to support imminent or future conservation actions. Achieving heritage models that represent the geometrical alterations of the assets has a direct impact on the accuracy of the analyses and simulations that can be carried out on the assets [11]. In contrast to excessively simplified modelling approaches, wall thicknesses and tilt can be accurately represented. This, taking into account the considerable deformations of Ye Olde Trip to Jerusalem and its cave rooms, should provide conservation stakeholders with insight into its special indoor thermal conditions. Consequently, condition monitoring of historic buildings can benefit from 3D laser scanning since their geometry and some key features and components can be identified for the purpose of retrofitting, cataloguing, or fully or partially reconstructing the building.

From the literature review, it was detected that point clouds, as the raw data from TLS technology, enable a general visual representation but cannot distinguish between detailed components and sub-structures in a true 3D CAD model. Hence, to achieve a 3D CAD model from point cloud data, manual or semi-automated techniques will be needed. This chapter discusses and evaluates point cloud-based modelling approaches that can be adopted in historic buildings and sites to construct the as-built 3D heritage models in CAD software. As indicated in this chapter, this can support the creation of HBIM projects for heritage conservation. In this sense, as-built 3D heritage modelling should be considered a pre-requisite for non-destructive monitoring strategy to retrofit and maintain building components.

Besides, these as-built 3D heritage models enable the creation of interactive and immersive technologies such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) for the exploration and dissemination of the assets. In fact, there are multiple commercial programmes compatible with the 3D mesh and solid models produced in this research.

Finally, given the current dependence on manual tasks when 3D modelling heritage assets with such complex geometries, future work will address the optimisation of 3D point cloud processing and advance the automation of the digital reconstitution from remote sensing data using machine learning. It is expected that this will contribute to the virtual reconstruction of heritage buildings, sites, and artifacts to allow specialists in the field to study them in detail, build knowledge from that, and disseminate the heritage assets to raise public awareness of their importance today and in the future.

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