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COMPARISON OF 3D REALITY CAPTURE TECHNOLOGIES FOR THE SURVEY OF STONE WALLS

COMPARATIVA DE TECNOLOGÍAS 3D PARA LA INSPECCIÓN DE MUROS DE PIEDRA

Enrique Valero^{a,*}, Alan Forster^a, Frédéric Bosché^a, Lyn Wilson^b, Alick Leslie^b

^a Royal Academy of Engineering Centre of Excellence in Sustainable Building Design, Heriot-Watt University, EH14 4AS, Edinburgh, UK. e.valero@hw.ac.uk; a.m.forster@hw.ac.uk; f.n.bosche@hw.ac.uk

^b South Gyle Conservation Centre, Historic Environment Scotland, EH12 9EB, Edinburgh, UK. lyn.wilson@gov.scot; alick.leslie@gov.scot

Abstract:

The maintenance of the external fabric of historic buildings constitutes a large portion of overall building life cycle costs. Advanced reality capture and data processing technologies have the potential to transform existing survey practice, providing surveyors with objective data pertaining to building fabric, in a more rapid (frequent), safe and cost-effective manner. In this paper, we present a unique evaluation of several Terrestrial Laser Scanning (TLS) and photogrammetric (PG) systems that assess their relative strengths for the survey of stone walls. The assessment is conducted using an historic building selected for its representativeness of form, fabric and condition. The work considers performance in terms of data accuracy and precision, data completeness, and process efficiency. The results show that, while TLS provides good geometric data to generate accurate and valuable 3D models, the quality of PG reconstructions can be also be sufficient in such contexts. And considering the relatively low-cost and portability of modern digital cameras compared to laser scanners, photogrammetry can constitute a realistic alternative to TLS. In addition, mounting a camera on a UAV could further solve access issues, preventing the need for any additional infrastructure (e.g. scaffolding), which would be required when employing TLS. However, a lesson drawn from this work is that effective acquisition of photogrammetric data requires careful planning to select the appropriate camera settings and picture density (and locations) to ensure accurate and reliable photogrammetric reconstruction. This process may be referred to as: *Planning for Photogrammetry (P4P)*.

Key words: virtual archaeology, historic buildings, cultural heritage, documentation, survey, 3D reconstruction, laser scanning, photogrammetry

Resumen:

Las labores de mantenimiento de la estructura externa de edificios históricos constituyen una gran parte de los costes asociados al ciclo de vida de estos. Las tecnologías empleadas para la adquisición de datos estructurales y su procesamiento tienen el potencial de transformar, en gran medida, las tareas de inspección tradicionales, proporcionando información relativa al edificio de una manera más rápida, segura y económica. En este trabajo, se evalúan escáneres láser y sistemas basados en fotogrametría, demostrando su solidez para la inspección de paredes de piedra. Esta evaluación se ha llevado a cabo en un edificio histórico representativo y en un buen estado de conservación. En el artículo, se compara la actuación de los diferentes dispositivos en términos de precisión, repetibilidad, densidad de datos y eficiencia del proceso. Los resultados muestran que, mientras que los escáneres proporcionan buena información geométrica y permiten la generación de modelos tridimensionales precisos, la calidad de las reconstrucciones a partir de fotogrametría también pueden ser suficientes en determinados contextos. Considerando, además, el relativo bajo coste y la portabilidad de las cámaras digitales modernas en comparación con los escáneres láser, la fotogrametría puede constituir una alternativa real a estos últimos. Además, la instalación de cámaras en vehículos aéreos no tripulados (drones) puede resolver problemas de accesibilidad y minimizar el uso de infraestructuras adicionales (como andamiajes), las cuales son empleadas en la digitalización mediante escáneres. Sin embargo, una lección que se desprende de estos experimentos es que para conseguir una efectiva adquisición de datos fotogramétricos se requiere una cuidada planificación y una selección apropiada de los ajustes de la cámara, así como su correcto posicionamiento en la escena, con el objetivo de conseguir una adecuada densidad de imágenes y obtener una reconstrucción 3D precisa. Este proceso se denomina *Planificación para la Fotogrametría*.

* Corresponding Author: Enrique Valero, e.valero@hw.ac.uk

Palabras clave: arqueología virtual, edificios históricos, patrimonio, documentación, inspección, reconstrucción 3D, escáneres láser, fotogrametría

1. Introduction

The maintenance of the external fabric of historic buildings constitutes a large portion of overall building life cycle costs. In Scotland alone, it is estimated that there are approximately 400,000 traditional (pre 1919) buildings representing 20% of building stock and constituting an important portion of construction spendings (Mueller *et al.* 2014). “*Repair, maintenance and improvement accounts for approximately 46% of the total construction industry output, of which one third relates directly to pre 1919 buildings (accounting for approximately £1.2 billion)*” (Historic Scotland 2011).

Environmental climatic conditions and associated weathering act as ‘agencies of materials change’, that lead to the deterioration of building fabric. Arresting this deterioration requires regular, appropriate maintenance. This operation is becoming more onerous due to climate change and more specifically increased incidence of extreme rainfall in Scotland. Practically, higher levels of moisture can be correlated with accelerated deterioration in porous building materials. Prevalent decay mechanism in masonry include increased severity and frequency in freeze-thaw cycling and spalling events, and biological growth associated with long term saturation of fabric. Logically, increased aggressivity of environmental conditions requires higher frequency evaluation of condition of the external envelope of buildings.

Maintenance decisions are made following detailed surveys of fabric. Advanced reality capture and data processing technologies have the potential to transform existing survey practice, providing surveyors with objective data pertaining to building fabric, in a more rapid (frequent), safe and cost-effective manner. In particular, greater volume and better accuracy of information can support surveyors in ensuring objectivity and consistency when assessing condition. This is paramount as these surveys are utilised to develop repair strategies.

Surveying building fabric encompasses many disparate and interconnected components that require the acquisition of various types of data. Principally, amongst information is construction form and materials. Both of these first order survey objectives rely upon specific data including the dimensions/geometry and texture of the fabric components. Advanced three-dimensional and visual reality capture technologies have been developed in the last few decades to acquire such data. These technologies mainly include: *photogrammetry* and *laser scanning*. Both can deliver dense 3D point clouds of scenes, possibly augmented with colour information. Photogrammetric systems are based on the use of cameras and the principle of stereo vision, while laser scanning is a more recent technology that is based on the controlled command of laser beams and time-of-flight principles to determine the distance to an object.

Despite the quality of the data delivered by laser scanners, their use is limited by the need to set up the scanner on the ground or a stable platform at multiple

locations that produce a complete 3D model when individual scans are registered together. Photogrammetric systems have shown great potential to resolve access-related issues but their performance can be significantly limited by the texture and/or type of material being scanned. Another limitation of photogrammetric systems is that the 3D data they provide has unknown scale; control networks or known dimensions in the data are necessary to convert the data to metric scale, which inevitably introduces additional error.

The different strengths and weaknesses of both systems have led researchers to determine which solution is most appropriate in various contexts. In this paper, we present a unique evaluation of several Terrestrial Laser Scanning (TLS) and photogrammetric (PG) systems that are compared to assess their relative strengths for the survey of stone walls. The assessment is conducted using an historic building selected for its representativeness of form, fabric and condition. The work considers performance in terms of data accuracy and precision, data completeness, and process efficiency.

This paper is structured as follows: Section 2 contains a review of prior works on the use of laser scanning and photogrammetry for the survey of historic buildings, leading to the identification of the knowledge gap that this research contributes to fill. Section 3 describes the technologies assessed and the methodology followed to compare them. Section 4 presents the on-site data acquisition and reconstruction steps. Section 5 reports and analyses the results on the comparison of the data obtained for the different systems. Finally, Section 6 presents the conclusions and future works.

2. Background

Laser scanning is a relatively recent technology that constitutes a revolution in land and building surveying. Within the context of historic monument survey, noteworthy examples of the use of TLS include the work of Wilson *et al.* (2013) who illustrate the advantages of TLS for the survey of large and complex historic monuments via case studies of UNESCO World Heritage Sites. Cardaci *et al.* (2011) show that TLS provides significant value compared to traditional manual survey. They also show how CAD models generated from the data can be successfully used for structural analysis using the Finite Element Method (FEM). Nettley *et al.* (2013) use TLS and light Detection and Ranging (LiDAR) – i.e. aerial laser scanning – to obtain a photorealistic geospatial model of the historic quayside at Cotehele Quay integrated in an accurate Digital Elevation Map (DEM) in order to assess the potential impact of rising sea levels resulting from climate change. Temizer *et al.* (2013) show the value of TLS to survey underground structures like the Byzantine cistern situated beneath the court of the Sarnicli Han building. They also investigate the impact of various levels of point filtering on the accuracy of the mesh produced from the data.

Photogrammetry is another well-established method for obtaining 3D records of historic monuments as the review of Ogleby (1995) for example shows. Its use outdates that of TLS by decades, almost a century (Schermerhorn 1940). However, significant progress has been made in the last two decades, both in terms of hardware and software, that has enabled significant automation of PG data acquisition and processing for 3D model reconstruction. The development of robust automated feature detection and matching in digital images, (e.g. SIFT (Lowe 1999) or SURF (Bay *et al.* 2006) features), as well as dense matching approaches (Strecha *et al.* 2003) have dramatically improved, even automated the image processing stage. Furthermore, high-resolution and portable digital cameras are now widely available at a relatively low cost, meaning that photogrammetry can be easily deployed to produce dense textured 3D point clouds and meshes. Thanks to the light weight of modern cameras, single-camera photogrammetry has also shown great potential to resolve access-related constraints.

Regarding the field of historic monument survey, remarkable examples of the use of photogrammetry include the work of Cappellini *et al.* (CAPELLINI, V., STEFANI, C., NONY, N. and DE LUCA, L., 2012) who apply it to produce 3D models of monuments that are used to generate 2.5D orthophotos of walls. Using the example of Roman walls, these orthophotos are employed to conduct the semantic annotation of the opus of different sections of the wall. Lerma and Muir (2014) present a comparison of laser scanning with photogrammetry, reconstructing a 3D model by means of Visual Structure for Motion (VSfM) and Patch or Cluster based Multi View Stereo Software (PMVS/CMVS), and concluded that for accurate documentation of carved detailing on stone, photogrammetric techniques provided the greatest level of flexibility and reliability, although the two techniques used in combination may provide the best results.

However, PG systems also have limitations. For example, they are not robust to varying lighting conditions and texture-poor or reflective materials (Thornbush and Viles 2008). Furthermore, their precision quickly drops with the distance of the camera to the target scene when compared to TLS (Rasztovtovs and Dorninger 2013). Also, single-camera PG systems provide 3D reconstructions only up to scale, and require the user to use survey networks or extract known dimensions in the images to adequately scale the reconstructions (Skarlatos and Kiparissi 2012).

With regard to access provision, PG and TLS systems can both be mounted on poles or extendable tripods that enable positioning them at heights up to approximately 5m. For greater heights, aerial solutions can then be considered. In fact, aerial photogrammetry and LiDAR (i.e. aerial laser scanning) systems have long been conducted using planes or helicopters with the sensors mounted under them. However, these solutions do not allow the acquisition of images at close distances, which limits the accuracy and density of the resulting 3D reconstructions. Recent and rapid developments of Unmanned Aerial Vehicles (UAVs), in particular helicopter-type UAVs, offer new platforms that are particularly suited to light-weight PG systems. PG cameras mounted on helicopter UAV enable the

acquisition of images at close ranges at any height, providing a serious advantage over laser scanning systems in terms of access provision. It should be noted that there are attempts to mount laser scanning systems on helicopter UAVs but the weight of the scanners requires very large UAVs and ensuring that the acquired data has high precision and accuracy remains a great challenge.

UAVs have already been considered for use in the application of photogrammetry in the context of historic monuments. For example, Püschel *et al.* (2008) propose the use of terrestrial and UAV pictures to create an accurate 3D model of Castle Landenberg. Remondino *et al.* (2011) review the different stages of data acquisition and processing, such as: planning, camera calibration, 3D reconstruction and applications; and Remondino (2011) provides an extensive review of devices and software for recording and modelling oriented towards cultural heritage. Lately, Koutsoudis *et al.* (2014) proposed a PG system combining UAV and terrestrial pictures and compared the resulting reconstruction with that obtained with TLS, reporting promising results. In contrast, Xu *et al.* (2014) actually combined 3D data from TLS and a UAV-mounted camera for the reconstruction of a historical monument in Fujian, China. TLS point clouds are used to model the façades and photogrammetric information is used to complete the roof area (not completely visible by the TLS system located on the ground).

Despite the greater effort invested into investigating the potential of TLS and PG for the survey of historic monuments, we found that further studies were still necessary to compare the quality of the data delivered by these technologies in the specific but common case of stone walls recording. In particular, the team wished to assess whether UAV-based photogrammetry could be used as a reliable means to obtain sufficiently accurate textured 3D models of masonry walls for their survey and maintenance, as such solution would considerably reduce the need for and therefore the cost and safety risks associated with traditional solutions for access provision (e.g. scaffolding, abseiling).

3. Methodology

The comparison of 3D reality capture technology was conducted experimentally in the field using an actual historic monument as test site. The study considered: two terrestrial laser scanners employing different measurement principles; a hand-held/pole-mounted single-camera PG system; and a UAV-mounted single-camera PG system.

This section first presents the characteristics and settings of the tested systems (Section 3.1). The test site and the reasons for its selection are described in Section 3.2. Finally, the criteria defined to compare the performances of the different systems are presented in Section 3.3.

3.1. Systems

The two TLS devices considered are the Leica ScanStation P40 and the Faro Focus 3D. The Leica ScanStation P40 (hereafter *TLS-1*) is the latest time-of-flight (TOF) scanner produced by Leica. It can scan objects up to 270m away, with an accuracy of 3mm at

50m and up to 1 million points are recorded per second (Leica Geosystems 2015). In contrast, the Faro Focus 3D (TLS-2) is a phase-based scanner. Its advertised performance (Faro 2011) characteristics show that this scanner can measure distances up to 120m, with slightly lower but still good single point precision (2mm at 25m) and can scan up to 1 million points per second. An additional important advantage of the Faro Focus 3D scanner is that it is significantly smaller and lighter weight than scanners such as the Leica ScanStation P40, which makes it more portable.

The first single-camera PG system considered (hereafter *PG-1*) is a digital single-lens reflex (DSLR) Nikon D810 camera equipped with a 14mm lens that is operated manually hand-held or mounted on an extendable pole. This camera can acquire 36 megapixel (MPx) pictures and the system allows the acquisition of high-quality data with the camera raised at heights up to 5m (the pole height). The second single-camera photogrammetric system considered (hereafter *PG-2*) is a DSLR Sony α -7R camera equipped with a 35mm lens that is mounted on a UAV and operated remotely. This camera can also obtain 36MPx pictures. The UAV on which the camera is mounted is an Asctec Falcon 8 Multi-rotor that can fly at significant distances and heights – although the pilot should continuously maintain eye contact, and Civil Aviation Authority regulations actually prevent flying such UAVs at heights above 120 metres.

3.2. Test Site

The East garden of the medieval Craigmillar Castle, in Edinburgh, Scotland, was selected as test site. This castle was built in the 14th century and is currently managed and maintained by Historic Environment Scotland. Within the East garden, the rampart wall (facing East; see Figure 1) was selected for the following reasons:

1. Complexity: The area of wall was selected due to its relative complexity and more specifically: the random nature of the stonework; variation in width and depth of mortar joint; planar and curved surfaces; stone soiling and associate colour and texture variation.
2. Sufficient height: It is important to study the performance of the chosen technologies at increasing heights; the rampart wall is approximately 10m high, which seemed sufficient to challenge certain technologies, in particular the ground-based TLS devices.
3. Wind protection: The UAV can only be operated in conditions with low wind (to prevent collision with the monument and ensure good quality pictures). To enhance the chances of being able to operated the UAV on the selected day for data acquisition, the East-facing wall was found best due to the predominantly western winds in Edinburgh;
4. Accessibility: There should not be trees or other occlusions preventing the safe use of the UAV and occluding the surveyed scene. The East-gardern does not include any trees.

3.3. Performance Assessment Criteria

The performances of the four 3D reality capture systems for the recording of the 3D geometry of stone walls were assessed and compared using several quantitative and qualitative criteria.

Data Completeness: this is measured by the density and uniformity of data across the acquired surface.

Efficiency: this is measured by the time required for acquiring and pre-processing the data to obtain a unified geo-referenced dense 3D point cloud.

Data Accuracy and Precision: taking the most accurate and precise TLS data as 'ground truth', data accuracy and precision is measured by the 'distance' of the other datasets to this ground-truth dataset. It is proposed to measure the 'distance' between two point clouds using the Hausdorff distance metric (Huttenlocher *et al.* 1993). For this, the volume containing the wall data is divided in voxels (i.e cuboids); we use voxels of size 1cm x 1cm x 10cm. The larger voxel side corresponds to the depth (perpendicular to the wall plane); it is set large to ensure matching points are found despite possible global misalignments. Note that the Hausdorff distance differs from the standard point-to-point distance that simply considers the closest points in the two point clouds. In contrast, the Hausdorff distance is based on the study of minimal and maximal distances between point clouds within each voxel, which makes it more sensitive to noisy data. Interestingly, it also makes it sensitive to variations in the uniformity of the cloud point density.

4. Data Acquisition and Reconstruction Stages

A survey network, composed of three geo-referenced tie points set with 150mm circular targets, was established within the East garden site for geo-referencing the TLS data. Unfortunately, such survey network cannot be used for the geo-referencing of PG data. This is due to the inability of the surveyors (and the technologies employed) to simultaneously focus the camera on the wall and the tie point targets located in the garden. Therefore, a second survey network based on a different set of geo-referenced targets had to be established with 17cm checkerboard patterns fixed to the walls. Both survey networks are shown in Figure 1. All measurements for the establishment of the networks were conducted using a Leica MS50 multistation.

To ensure a full coverage of the garden, three laser scans were acquired with TLS-1, with a resolution of 1.6mm at a range of 10m. The three scans were then aligned using the TLS survey network, resulting in a unified clean point cloud containing 374 million points, including 180 million points from the rampart wall.

The same procedure was applied for the data acquisition using TLS-2, with three scans acquired at similar locations and with a resolution of 3mm at 10m. The final unified point cloud contained 87 million points overall, and 51 million points for the rampart wall section. In this case, colour information has also been acquired using the Faro Focus 3D internal camera.

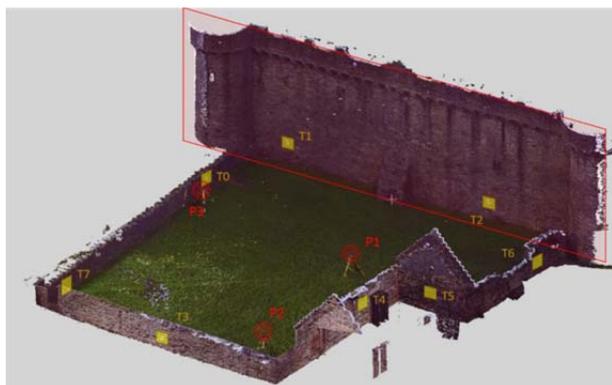


Figure 1: Point cloud of the East garden of Craigmillar Castle. The rampart wall is marked in red. The TLS survey network is illustrated in red, and the PG network in yellow.

Using the PG-1 system, 260 pictures were taken from many locations around the garden and with different orientation. The distance of the camera to the walls was kept to approximately 5m, with a few additional pictures taken at further distances. While some of the images were acquired with the camera hand-held, other images (specifically for the rampart wall) were acquired with the camera mounted on the pole and triggered using a mobile phone app. An overlap of 40-50% between adjacent photos was aimed for. The 3D reconstruction was conducted using Agisoft PhotoScan v.1.1.6, delivering a dense point cloud containing 79 million points overall, including 51 million points for the rampart wall section. The PG-1 point cloud was scaled and geo-referencing using the PG survey network.

Using the PG-2 system, 460 pictures were acquired at similar distances to the walls. The pictures were then processed using the exact same procedures as for the PG-1 system, delivering a geo-referenced and scaled dense point cloud containing 34 million points overall, including 20 million points for the rampart wall section. The reconstruction process used for both photogrammetric reconstructions (PG-1 and PG-2) integrates the optimisation of the camera internal calibration, and this process is carried out using as initial values those provided by the manufacturers (EXIF information).

The point clouds corresponding to the rampart wall for all these reconstructions are shown in Figure 2. Note that the colour information was acquired with the TLS-2 system but not TLS-1 system. Nonetheless, colour information appears of significantly better quality for the PG systems.

5. Results

5.1. Data Precision and Accuracy

For the reporting and analysis of the results on the accuracy and precision of the systems, we focus on three areas of the rampart wall that we found were representative in highlighting the strengths and limitations of the different survey technologies regarding accuracy and precision. These areas are shown in Figure 3. Area 1 is an upper part of the wall, at 5 meters height and its dimensions are 4m x 2m. Area 2 is located just below at human height and has similar dimensions.

Finally, Area 3 covers a vertical region, with dimensions 2m x 6m.

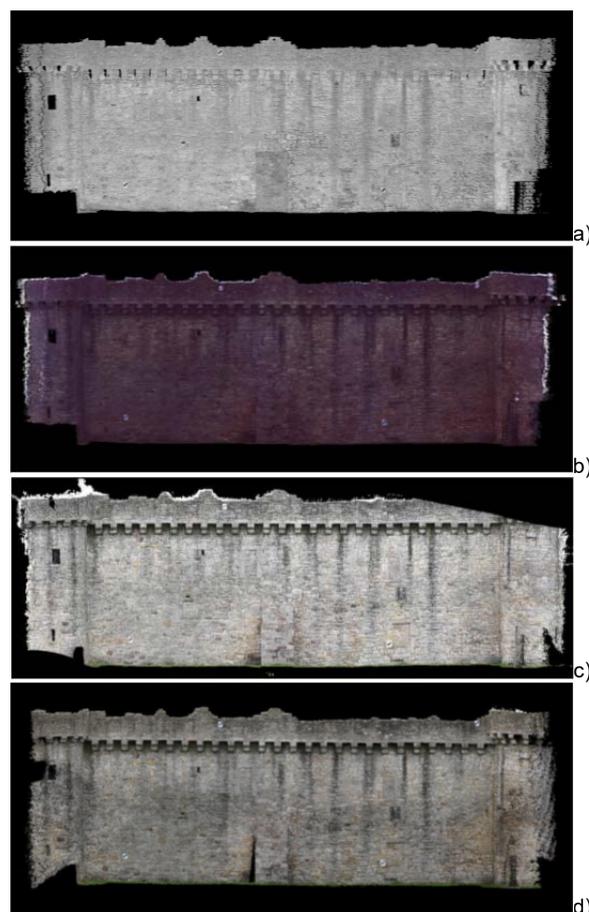


Figure 2: Wall reconstruction for the employed systems. (a) TLS-1, (b) TLS-2, (c) PG-1, (d) PG-2.

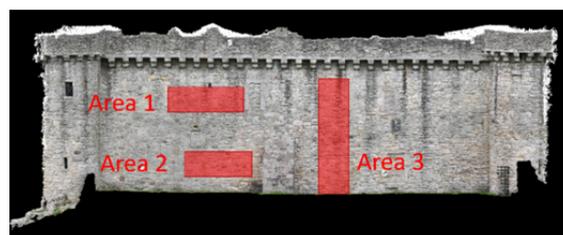


Figure 3: The three areas within the East rampart wall that are used for the assessment of performance in terms of accuracy and precision.

As previously mentioned, all the datasets were geo-referenced by means of survey networks. Given the matches between the tie points in the survey networks and the corresponding points in the acquired point clouds, the geo-referencing errors are calculated for all devices and summarised in Table 1.

These results, together with the better specifications of the TLS-1 device in comparison with TLS-2, lead to the conclusion that TLS-1 indeed provides the data with the highest quality overall and so can be used as *ground truth* against which all other datasets can be compared.

Table 1: Mean residual errors for the geo-referencing of the different devices.

Device	Value (inch)
TLS-1	1.53
TLS-2	3.73
PG-1	19.8
PG-2	18.1

Figure 4 illustrates the results of the Hausdorff distance calculations for the three selected areas of the rampart wall, and Table 1 summarizes the mean and standard deviations of the Hausdorff distance for each case. As can be seen, the Hausdorff distances are smaller for the Faro TLS with a mean below 5mm in both Areas 1 and 2. The mean distance for the PG-1 point cloud is only slightly higher and is thus remarkably good. In contrast, the results are disappointing for the PG-2 point cloud, with a mean between 10 and 20mm. The results are particularly poor for Area 1. But, we identified that this was due to the insufficient amount of overlap between neighbouring pictures acquired by the PG-2 system. The reasons for the poor performance of PG-2 are discussed further in Section 5.4.

Area 3 was selected to assess the variation of the accuracy and precision with height for the different systems. It is interesting to note the relative uniformity of the Hausdorff distances along the height of the wall for the PG-2 data which highlights the advantage of UAV in terms of access, thereby ensuring consistent results. For the pole-mounted PG-1 system, the distances increase more significantly at the bottom, because fewer images were taken of the lower parts – the operator was focused on the coverage of the upper part of the wall that is less accessible and did not realise that an insufficient number of images would be taken for the lower part (e.g. taking pictures while on their knees). However, the height of the wall (10m) seemed not to have been quite sufficient to show a similar pattern in the top part of the wall resulting from the limited extension of the pole. This suggests that even with a 5m pole, good-quality data can still be obtained up to almost twice that height.

Overall, these results confirm that TLS devices provide more precise and accurate results than photogrammetric systems. But, the cheaper pole-mounted PG-1 system demonstrated comparatively good results, meaning that such a system can certainly be considered as a reliable alternative for the survey of stone walls.

Table 2: Mean (μ_H) and standard deviation (σ_H) of the Hausdorff distance of the TLS-2, PG-1 and PG-2 point clouds against the TLS-1 point cloud, for the three selected Areas of the rampart wall.

Device	Area 1 (mm)		Area 2 (mm)		Area 3 (mm)	
	μ_H	σ_H	μ_H	σ_H	μ_H	σ_H
TLS-2	3.67	1.06	4.29	0.99	5.23	1.66
PG-1	4.36	1.60	5.09	1.95	6.14	2.8
PG-2	17.62	10.18	10.79	5.62	7.76	3.04

5.2. Data Completeness

Performance cannot be solely judged on data precision and accuracy. Another important criterion is data completeness, that assesses data point density and its uniformity. Table 3 summarizes the point density in the point clouds obtained for the entire rampart wall by means of the four different systems. Point density is calculated by projecting the reconstructed points on the wall plane and then calculating the density of points within that plane. As can be seen, the density is higher for the laser scanners, but again we note that the difference between the TLS-2 and PG-1 systems is really not that significant, which further confirms the potential of PG-1 system as an alternative 3D reality capture technology.

Table 3: The maximum density (Max_D), mean density (μ_D) and standard deviation (σ_D) for the point clouds of the entire rampart wall obtained by the four reality capture systems.

Device	$MaxD$ (pts/cm ²)	μD (pts/cm ²)	σD (pts/cm ²)
TLS-1	164	75.94	11.67
TLS-2	49	22.99	3.88
PG-1	31	16.09	3.05
PG-2	23	7.54	2.29

5.3. Process Efficiency

An additional criterion for comparing performance between TLS and PG systems is efficiency. This is defined as the time required for acquiring and processing the data to obtain a unified geo-referenced dense 3D point cloud. Acquisition time comprises the positioning of the devices around the garden and the acquisition of points clouds (for TLS devices) or pictures (for PG systems). Processing includes data transfer, registration/geo-referencing, colourisation and data cleaning (removing spurious data).

Table 5 shows the approximate time recorded for each task for each survey system. Note that the processing operations have all been undertaken on the same computer (i7 3.60GHz processor and 12 GB RAM). Regarding the acquisition stage, the scanning time appears significantly shorter for the TLS-1 than for the TLS-2. But, this is essentially due to the fact that no colour information was acquired during the TLS-1 scanning. If colour acquisition had been conducted, the acquisition times would likely have been similar. An important difference is noticeable between PG-1 and PG-2. This is due to two factors. First, the longer focal length selected for the PG 2 system led to the need to acquire many more images with the PG-2 system (to ensure sufficient overlap between neighbouring images). Then, the UAV could only work for 10-minute periods at a time, after which the UAV had to be landed to change its battery before resuming works. Combined, these two factors resulted in a significantly longer acquisition time than expected for the PG-2 system. The analysis of the performance of the PG-2 system is further discussed in Section 5.4.

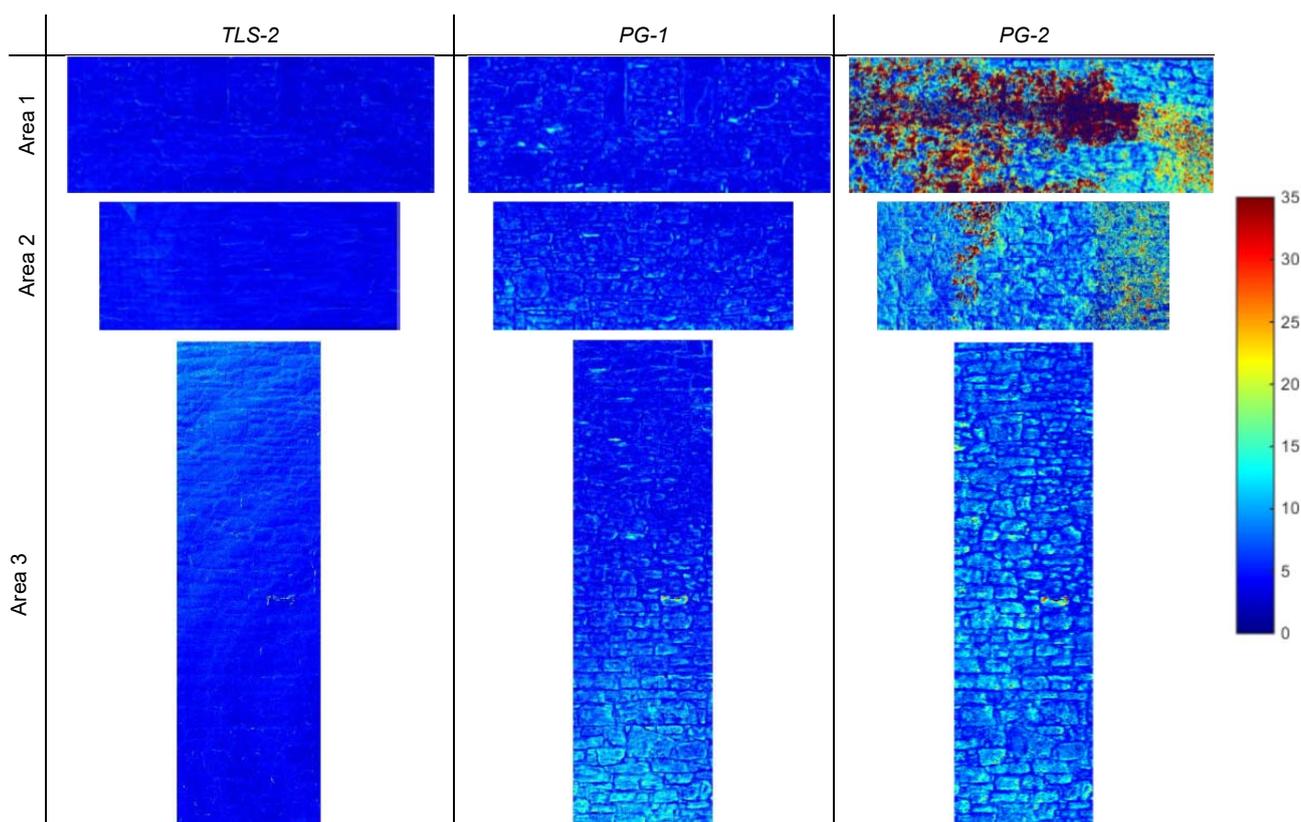


Figure 4: Hausdorff distance between Leica ScanStation P40 point cloud and the point clouds of Faro (left), Nikon (middle) and Sony (right) for the three selected Areas of the rampart wall.

Processing times are similar for all systems, despite the fact that they require different processing steps. The main observation is that processing times are in this case study often more than double the acquisition times, despite the use of a high-performance computer.

Table 4: Acquisition and pre-processing times for TLS and PG systems.

	Acquisition	Processing	Total
TLS-1	40'	3 h	3h 40'
TLS-2	1h 30'	2 h 30'	4 h
PG-1	30'	3 h 15'	3 h 45'
PG-2	1h 30'	3 h 15'	4 h 45'

5.4. Discussion of the Performance of the UAV-based PG System (PG-2)

Reasonably good quality results were achieved with the PG-1 system, suggesting that in such contexts photogrammetric systems can be considered as viable alternatives to TLS. It was hoped that similar results would also be achieved with the PG-2 system that would have demonstrated its additional advantage in terms of access provision. Yet, the results achieved with the PG-2 system were comparatively very poor and disappointing overall. It must however be qualified that, in some areas of the wall, the results obtained with the PG-2 system were as good (if not better) than those obtained with the PG-1 system. This section aims to discuss the reasons for these poor results observed in certain areas, highlighting the factors that contributed to

getting those poor results, and how they could in fact have been obviated. This shall demonstrate that UAV-based PG systems do have great potential for the survey of stone walls, as long as the identified factors are adequately managed.

The local variability in the quality of the reconstruction obtained with the PG-2 has highlighted that (1) camera locations, and (2) camera properties and settings can significantly impact the performance of those systems. PG-1 and PG-2 actually used different camera setups and camera positioning methods, which we believe altogether explain the poorer results achieved by PG-2.

Firstly, Table 5 shows that the camera settings of PG-1 and PG-2 differed in several ways. The PG-2 system did not use entirely manual settings, which led to images with varying ISO and F-stop values. But, an important difference is noticed in the lens's focal length. The focal length of PG-2 is three times larger than that of PG-1, which implies that the wall area covered by each picture taken by the PG-2 system was significantly smaller. The ground sampling distance (GSD) for each system can be obtained from the parameters presented in Table 5. For PG-1, GSD=2mm; for PG-2, GSD=0.5mm. To ensure a sufficient amount of overlap between pictures, a significantly larger number of images was thus necessary. Although twice more pictures were indeed acquired using the PG-2 system compared to PG-1, this number appears to still have been insufficient. Indeed, the poor quality of the reconstructions achieved in the local areas of the rampart wall Area 1 and Area 2 visible in Figure 4 appears to directly correlate with a lower overlap between images acquired with the UAV in these areas, as can be seen in Figure 5.

Table 5: Properties and settings of the cameras used in the two PG systems.

Settings	PG-1	PG-2
Size (px)	7360 x 4912	7360 x 4912
Sensor (mm)	35.9 x 24	35.9 x 24
Focal length (mm)	14	35
F-stop	f/8	f4-f/8
ISO	250	100-400
Shutter (s)	1/125	1/500
Number of pictures	260	460
Area of wall covered by the camera at 5m (m)	15.5 x 10.3	4 x 2.7

**Figure 5:** Camera locations (in blue) for the acquisition of data with the PG-2 system. The three areas of the wall used for the performance assessment are shown in red.

The PG 2 system operators may have expected that, by acquiring more images with a lens having a longer focal length, better results would be produced. But, they underestimated the full impact of a longer focal length on the number of images needed to be acquired. In this case, it seems that they should probably have acquired twice more pictures than they actually have (which would have further negatively influenced the acquisition time). Naturally, other factors may have influenced the results, such as the variable F-stop and ISO values. But, we found the PG-2 pictures to be of quality similar to that of the PG-1 system. This suggests that, thanks to their modern gimbals, UAVs can provide a reliable platform for the acquisition of images for photogrammetric purposes.

Overall, we believe that significantly better results (at least as good as PG-1) would have been obtained by using a lens with short focal length (14-16mm) on the UAV-mounted camera (PG-2). A more general lesson drawn from this work is that careful planning should be considered to select the appropriate camera settings and picture density (and locations) to ensure accurate and reliable photogrammetric reconstruction. This process may be referred to as: *Planning for Photogrammetry (P4P)*.

6. Conclusions

Terrestrial laser scanning and photogrammetry are increasingly used for building surveying, providing dense textured 3D point clouds (and meshes). In terms of geometry, data from TLS was found particularly accurate. While this was expected (since it had been shown by previous researchers), in the case study considered here the Faro Focus 3D scanner point clouds were close to the Leica ScanStation P40 ones. This

similarity is interesting, although it must be remembered that these results are obtained at rather short ranges (maximum 10m) and the performance of the Faro scanner would be expected to deteriorate faster at larger distances.

While TLS clearly provides good geometric data to generate accurate and valuable 3D models, it also has three important limitations. First, TLS devices remain relatively expensive (tens of thousands of pounds per unit). Also, the cameras embedded within the scanners do not produce good quality colour information compared to what is achieved with common DSLR cameras. And finally, but still very importantly, current TLS devices have to be operated from stable positions, which reduces their mobility and the range of contexts within which they can be reliably employed.

In contrast, modern digital cameras are relatively cheap and very portable, making them suitable in a wider range of contexts. However, their main limitation is their variable performance depending on the level of texture in the scene being reconstructed. Nonetheless, we have shown that scenes like stone walls present great textures for the application of photogrammetry. In such contexts, photogrammetry can constitute a realistic alternative to TLS.

Mounting a camera on a UAV can further solve access issues. A copter-type UAV can fly around close to buildings and take pictures from different viewpoints without the need for any additional infrastructure (e.g. scaffolding). This theoretically extends the applicability of photogrammetry to significantly more contexts (e.g. without occluded areas, as was experienced with TLS). Unfortunately, this research was not able to fully demonstrate this. However, the analysis of the factors that led to the disappointing results obtained with the UAV-mounted PG system were 'simply' an inappropriate selection of lens and a correspondingly insufficient number of images acquired. The results showed the need for photogrammetric survey teams to have a good understanding of the photogrammetric process to establish effective data acquisition procedures. This suggests the need to establish robust methods for *Planning for Photogrammetry (P4P)*, which should be the focus of future investigations. But, the results reported here should not deter professionals from considering this otherwise valuable technology that could significantly reduce the cost and safety risks associated with access provision, in comparison with current solutions used for manual survey as well as the use of TLS systems.

Beyond the technical conclusions provided, this work also highlights that mixed adoption of technologies or specific technologies utilised for survey are potentially required. Their selection will depend upon weighted considerations for data precision, acquisition and processing efficiency, and health and safety grounds. The work shows that it is important that surveyors attempt to better understand the pros and cons of technologies adopted and realise that some will perform better than others in different contexts. It stresses that better dialogue between traditional surveyors and architects and specialist technologically-oriented survey operatives is required so that better understanding of expectations can be achieved by both parties.

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References

- BAY H., TUYTELAARS, T and VAN GOOL, L., 2006. SURF: Speeded Up Robust Features, *Proceedings of the 9th European Conference on Computer Vision*, Part I, Graz, Austria, pp. 404-417.
- CAPELLINI, V., STEFANI, C., NONY, N. and DE LUCA, L., 2012. Surveying Masonry Structures by Semantically Enriched 2.5D Textures: A New Approach. In M. IOANNIDES, D. FRITSCH, J. LEISSNER, R. DAVIES, F. REMONDINO and R. CAFFO, eds, *Progress in Cultural Heritage Preservation*, Vol. 7616 of *Lecture Notes in Computer Science*, Springer Berlin Heidelberg, pp. 729–737. DOI: 10.1007/978-3-642-34234-9_77
- CARDACI, A., ROBERTI, G. M. and VERSACI, A., 2011. From the Continuous to the Discrete Model: a Laser Scanning Application to Conservation Projects. In *Proceedings of the Congress of the International Society for Photogrammetry and Remote Sensing (ISPRS) 2011*, Trento, Italy, pp. 437–444.
- FARO, 2011. Faro Focus 3D 120 Specifications. Available: <http://www.faro.com/products/3d-surveying/laser-scanner-faro-focus-3d> [1/26, 2016].
- HISTORIC SCOTLAND, 2011. Scottish Traditional Building Skills. Audit Scoping Exercise. Technical report, Historic Scotland.
- HUTTENLOCHER, D., KLANDERMAN, G. and RUCKLIDGE, W., 1993. Comparing Images Using the Hausdorff Distance. *IEEE Transactions on Pattern Analysis and Machine Intelligence* **15**(9), pp. 850–863. DOI: 10.1109/34.232073.
- KOUTSOUDIS, A., VIDMAR, B., IOANNAKIS, G., ARNAOUTOGLU, F., PAVLIDIS, G. and CHAMZAS, C., 2014. Multi-Image 3D Reconstruction Data Evaluation. *Journal of Cultural Heritage* **15**, pp. 73–79. DOI: doi:10.1016/j.culher.2012.12.003.
- LEICA GEOSYSTEMS, 2015. Leica ScanStation P30/P40 Specifications. Available: http://w3.leica-geosystems.com/downloads123/hds/hds/general/brochures-datasheet/Leica_ScanStation_P30-P40_Plant_DS_en.pdf [1/26, 2016].
- LERMA, J. and MUIR, C., 2014. Evaluating the 3D Documentation of an Early Christian Upright Stone with Carvings from Scotland with Multiples Images. *Journal of Archaeological Science* **46**, pp.311–318. DOI: doi:10.1016/j.jas.2014.02.026.
- LOWE, D., 1999. Object Recognition from Local Scale-Invariant Features. In *Proceedings of the Seventh International Conference on Computer Vision*, 1999, Kerkyra, Greece, Vol. 2, pp. 1150–1157.
- MUELLER, G., ROBERTSON, J., LEADBETTER, C., LAING, N., MCMENEMY, M. and KYRIAKOU, A., 2014. Scottish House Conditions Survey 2013. Key Findings. Technical report, Directorate for Housing, Regeneration and Welfare. Scottish Government.
- NETTLEY, A., ANDERSON, K., DESILVEY, C. and CASELDINE, C., 2011. Using Terrestrial Laser Scanning and LIDAR Data for Photo-Realistic Visualization of Climate Impacts at Heritage Sites. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, **38**, pp. 223–229. DOI: 10.5194/isprsarchives-XXXVIII-5-W16-223-2011.
- OGLEBY, C. L., 1995. Advances in the Digital Recording of Cultural Monuments. *ISPRS Journal of Photogrammetry and Remote Sensing* **50**(3), 8 – 19. DOI:10.1016/0924-2716(95)91286-S.
- PUSCHEL, H., SAUERBIER, M. and EISENBEISS, H., 2008. A 3D Model of Castle Landenberg (CH) from Combined Photogrammetric Processing of Terrestrial and UAV-Based Images. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **37**, pp. 93–98.
- RASZTOVITS, S. and DORNINGER, P., 2013. Comparison of 3d Reconstruction Services and Terrestrial Laser Scanning for Cultural Heritage Documentation. *XVI International CIPA Symposium*, 2013, Strasbourg, France, Vol. 1, pp. 513–518.
- REMONDINO, F., 2011. Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning. *Remote Sensing* **3**, pp. 1104–1138. DOI: 10.3390/rs3061104.
- REMONDINO, F., BARAZZETI, L., NEX, F., SCAIONI, M. and SARAZZI, D., 2011. UAV Photogrammetry for Mapping and 3D Modeling - Current Status and Future Perspectives. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **38**, pp. 25–31.
- SCHERMERHORN, W., 1940. Draft for an International Bibliography of Photogrammetry, *Photogrammetria* **3**(3), pp. 116 – 119. DOI: 10.1016/S0031-8663(40)80036-7.

- SKARLATOS, D. and KIPARISSI, S., 2012. Comparison of Laser Scanning, Photogrammetry and Sfm-Mvs Pipeline Applied in Structures and Artificial Surfaces. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. I-3, pp. 299–304.
- STRECHA, C., TYUTELAARS, T. and VAN GOOL, L., 2003. Dense Matching of Multiple Wide-baseline Views. In *Proceedings of International Conference on Computer Vision, ICCV 2003*, Nice, France, Vol. 2, pp. 1194 - 1201.
- TEMIZER, T., NEMLI, G., EKIZCE, E., EKIZCE, A., DEMIR, S., BAYRAM, A., COBANOGLU, A. V. and YILMAZ, H. F., 2013. 3D Documentation of a Historic Monument Using Terrestrial Laser Scanning Case Study: Byzantine Water Cistern, Istanbul. In *XXIV International CIPA Symposium*, 2013, Strasbourg, France, pp. 623–628.
- THORNBUSH, M. J. and VILES, H., 2008. Photographic Monitoring of Soiling and Decay of Roadside Walls in Central Oxford, England, *Environmental Geology* **56**(3-4), pp. 777–787. DOI: 10.1007/s00254-008-1311-3.
- WILSON, L., RAWLINSON, A., MITCHELL, D., MCGREGOR, H. and PARSONS, R., 2013. The Scottish Ten Project: Collaborative Heritage Documentation. In *XXIV International CIPA Symposium*, Strasbourg, France, pp. 685-690.
- XU, Z., WU, L., SHEN, Y., LI, F., WANG, Q. and WANG, R., 2014. Tridimensional Reconstruction Applied to Cultural Heritage with the Use of Camera-Equipped UAV and Terrestrial Laser Scanner. *Remote Sensing* **6**, pp. 10413–10434. DOI: 10.3390/rs61110413.