Revealing the potentials of 3D modelling techniques; a comparison study towards data fusion from hybrid sensors

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Abstract. The vast advantages of 3D modelling industry have urged competitors to improve capturing techniques and processing pipelines towards minimizing labour requirements, saving time and reducing project risk. When it comes to digital 3D documentary and conserving projects, laser scanning and photogrammetry are compared to choose between the two. Since both techniques have pros and cons, this paper approaches the potential issues of individual techniques in terms of time, budget, accuracy, density, methodology and ease to use. Terrestrial laser scanner and close-range photogrammetry are tested to document a unique invaluable artefact (Lady of Hatra) located in Iraq for future data fusion scenario. Insight investigations of the factors affecting data processing and modelling in individual comparing techniques are discussed and analysed. Qualitative and quantitative statistical analysis was applied based on multiple criteria, such as level of automation (LOA), accuracy and point cloud integrity towards the adaption of data fusion approaches and co-registering frameworks for optimal deliverables.

Keywords: Terrestrial laser scanning, Close range photogrammetry, 3D modelling, Data analysis, Data fusion

1. Introduction

Cultural heritage (CH) has always been a vital part of humanity. It reflects the development of human societies throughout history, giving humans precious legacy and spiritual values from their ancestors. Despite its great importance, CH is often under different kinds of threats from human conflicts, disaster, tourism, mismanagement, etc [1]. Therefore, significant efforts have been put on conserving CH, including digital documentation, restoration, and reconstruction of artefacts and sites. Terrestrial Laser Scanning (TLS) and Close-Range Photogrammetry (CRP) are the most popular and prominent approaches used for such documentation tasks. However, due to specific requirements in different reconstruction projects and different characteristics of both methods, none of the sensors is superior over the other [2].

There have been numerous studies to investigate structure from motion (SFM) photogrammetry and TLS to record archaeological sites and objects. (Kersten, et al., 2006) [3] has addressed how CRP could be merged with computer vision approaches to achieve more detailed models comparing with TLS standalone technique which requires intensive processing procedures to preserve details. In terms of accuracy assessment, (T. Nuttens, et al., 2011) [4] has evaluated the relative metric accuracy of both techniques (CRP and TLS) by measuring a set of topographic control points using traditional techniques. The study came up with equal systematic errors in planimetry for both techniques, however, the Z-direction errors were higher with photogrammetry than with TLS. Nevertheless, every acquisition technique, i.e. TLS, CRP or conventional surveying methods present particular limitations...
due to different reasons, whether it concerns with sensor type or data type, they considered a complementary assets [5][2].

In this study, the terrestrial laser scanner (STONEX X300) and DSLR cameras have been tested to document an invaluable heritage artefact. The two sensors were deployed to produce a digital archive in form of 3D point clouds; thus, it requires to walkthrough impacting steps to reveal the potentiality of individual sensors and preserve clean, consistent and accurate deliverables. This paper is structured into six sections; sections (1) is an introduction followed by a definitive overview about the case study in section 2. Section (3) is dedicated to investigate CRP and address important insights with respect to camera settings, pre-processing photos, the photogrammetric solution to end up with reporting derived point clouds. In section (4), we have explored the TLS technique, highlighting filtering process, registration strategies and addressing the quality of resultant point clouds. Section (5) is devoted to conduct a comparative analysis to both sensors to point out the level of automation, geometric accuracy and data integrity. Eventually, discussions and conclusions are presented in section (6).

2. Case study
The Lady of Hatra (Figure 1) is the case study in this research. It is formally known as (Abu Bint Dimeon), the wife of king Sinutruk-I which is considered one of the finest pieces from Hatra city, which lies to the north of Iraq. The well-sculptured details reflect the creativity of artists from that era. The statue was found in the large temple of Hatra city among other statues of her family, dated back to the Hellenistic period (312-139 B.C.). The artefact is made of limestone, about (3*0.70*0.30) meters in dimensions and stored at the Iraqi national museum.

![Figure 1. Lady of Hatra (LoH) case study.](image_url)

3. Close range photogrammetry (CRP)
It is well known that today’s cameras are sophisticated enough to capture a sufficient amount of details which enables photogrammetric solutions to automatically reconstruct 3D models. However, it is necessary to bear in mind the effecting factors on acquiring high-detailed photos like illumination, camera settings, data format and so on. As well as, merging photography skills with photogrammetry was of great benefit in this work.

3.1. Shooting Sessions
A Canon DSLR camera (7D Mark-II) of 24-megapixel resolution and 18-50 lens, was used to capture the statue. Low value of shutter speed was utilized to deliver good exposure conditions; therefore, the camera tripod was necessary to avoid shaking defects. Three loops of photos (351 in sum) are captured.
to cover the entire statue details, which took more than 15 hours to accomplish photo capturing session. The camera was set to record images in RAW and JPEG formats.

3.2. Post-processing
Prior to 3D reconstruction, raw images have been pre-processed to be enhanced in terms of shadow reduction, realistic colors and details improvement which, in turn, enables SFM approaches to extract more details from images and resulting in better alignment, meshes, and textures. Datasets were processed in RealityCapture (RC) software to produce a photo-realism replica. The software is one of the prominent photogrammetric solutions available in the market which relies on the recent state-of-the-art approaches to process images and laser scans. Furthermore, RC utilizes parallel computing to extremely speed up processing pipeline, thus it doesn’t require high-end computers to deal with huge datasets [6].

There are three main stages executed in the photogrammetric software to reconstruct 3D models, those are alignment, meshing and texturing. To stitch sequential images together (alignment), sufficient overlapping area is a must where SFM operators could extract and match common features intelligently [7]. The process of alignment is entirely automated, though RC offers comprehensive options to manipulate settings in a way to derive dense, accurate and consistent point clouds. Figure 2 is the derived 3D point clouds out of images, along with a report provided by RC (table 1).

| Table 1. CRP alignment report provided by RealityCapture. |
|----------------------------------------------------------|
| Count of registered images | 349 |
| Automatic tie points (ATP) | 2 158 933 |
| Mean reprojection error [pixels] | 0.353692 |
| Point cloud count | 32 070 452 |
| Alignment time | 00h:20m:20s |

4. Terrestrial laser scanning (TLS)
The STONEX X300 3D laser scanner used in this study to 3D model the case study by laser scanning technique. The scanner is a pulse-detection system with range accuracy of less than 6mm at 50m and 40mm at 300m, in addition to two integrated cameras of 5-megapixel resolution.

![Figure 2. 3D point clouds model based on CRP technique.](image)
4.1. Scanning Sessions
According to a laboratory test, the minimum range to record laser reflectance in this scanner is 3 meters. Therefore, a circle of 3m-radius was drawn to determine the scanning path around Lady of Hatra. Nine scans have been collected to cover the statue. However, the place was not spacious enough to circle scanning.

4.2. Post-Processing
Automation of laser scanning processing has been always a topic of research as it involves painstaking efforts to be delivered in full and complete form. Post-processing aims to produce clean and registered point clouds; thus, it goes through two crucial stages, pre-processing and registration. JRC 3D Reconstructor 3 is the native software provided by STONEX which holds most processing operations of laser point clouds.

4.2.1. Pre-processing
STONEX has their own format (x3a) to decode laser scans so an initial conversion (to x3a) is mandatory to import datasets into 3D Reconstructor software. The software offers different filters to pre-process laser scans such as noise reduction, normal computation and masking. Filtering routines can be applied with the push of a bottom; however, it requires comprehensive understanding to obtain satisfactory results particularly for close-range scanning of complex details [8]. Laser scans were subjected to a high level of noise because of the short-range acquisition (3 meters) that necessitates intensive and time-consuming works to be denoised.

4.2.2. Registration
The process of combining (stitching) multiple scans in one coordinate system is called registration which results in a larger and contiguous point clouds of the entire scene. As stated earlier, this stage is crucial for the quality of final outcomes since registration errors propagate and accumulate with the individual point uncertainties. Registration errors also accumulate and distribute differently based on the registration strategy applied. Most of today’s laser processing software follow the coarse-to-fine registration strategy where point clouds are roughly aligned by selecting at least three common features between pairs of scans and then refined by running an automatic Iterative Closest Point (ICP) algorithm [9].

JRC 3D Reconstructor offers two automatic algorithms to refine registration; pair-wise registration (ICP registration) and global registration (LM-ICP with bundle adjustment). While the ICP registration works only for one pair of scans at a time, LM-ICP algorithm registers together multiple scans at once, distributing evenly the registration errors, hence, LM-ICP approach was adopted in this study. The advanced parameters of LM-ICP describe how the search distance for the registration is defined. The maximum search distance is the most essential parameter of the registration. It defines the threshold between points that must be aligned together (with distance below the threshold) and points that must be considered as belonging to different objects (with distance above the threshold). Roughly aligned scans have been refined by LM-ICP algorithm to result in (8mm) mean error. It is clearly seen in Figure 3 how LM-ICP dramatically reduces discrepancies by minimizing the inliers percentage and distributing errors among scans.

It is likely to face some misleading results in the registration report which delivers confusion for decision making in forthcoming processing stages. One of these misleading outcomes is that the sophisticated algorithms are likely to produce false positives (accepted registration errors but clearly mis-aligned scans). Moreover, commercial solutions do not clearly outline the way they measure registration quality. Consequently, it takes expertise to validate the results of registration. Figure 4 shows the complete points clouds after registration which have been cleaned and exported as E57 format.
5. Comparative analysis of CRP and TLS

Close Range Photogrammetry (CRP) and Terrestrial Laser Scanner (TLS) have been employed to conserve the Lady of Hatra in the form of point cloud archiving. Conducting objective comparison required intensive investigations for the acquisition and processing phases to unveil the pros and cons of each technology individually. Thus, the comparative analysis was done on different levels.

5.1 Level of automation (LOA)

Terrestrial laser scanners are often marked as fast-acquisition technology which produces multi-millions 3D points in few seconds, though, these point clouds require tedious and time-consuming post-processing to be delivered in a clean and consistent form. On the opposite side, photogrammetry requires more on-field efforts, tools, hundreds of photos and many hours to acquire an object within the size of LoH. Unlike laser scanning, photogrammetric solutions ensure automatic and user-friendly workflow to deliver desired outcomes. Figure 5 is an overview of the observed LOA throughout different steps in the laser scanning and photogrammetry processes. The percentage values depicted in the figure are assigned based on time-consumption, ease-to-use, level of experience and hardware utilization where (0%-20%) is considered a low grade of automation, moderate for (50%-60%) and high for (100%). It can be seen how CRP is less automated in terms of data acquisition and scaling while TLS is superior in these regards. Conversely, TLS is a time-consumer technique when it comes to registering scans and deriving 3D textured-meshes from point clouds.

![Figure 3. LM-ICP mechanism to minimize registration errors.](image3.png)

![Figure 4. Registered 3D scans from TLS technique.](image4.png)

![Figure 5. LOA investigations for CRP and TLS techniques.](image5.png)
5.2. Metric comparison

Range scanner (TLS) is a Time-Of-flight (TOF) technology which deploys speed of light \((3*10^8\ \text{m/sec.})\) and trilateration concepts to provide metric measurements in an arbitrary 3D coordinates system [10]. Contrary to laser scanners, photogrammetry delivers non-scaled point clouds because of the pixel system photos assigned to, which needs further steps in order to be transformed into a metric coordinates system. Scaling or as known geo-referencing was done using ground-truth measurements surveyed by Total Station (Topcon ES-105) with a range accuracy of 3mm.

Registration errors addressed in sections (3.2) and (4.2.2) give an impression about the precision of deriving point clouds (in case of CRP) or aligning scans (in case of TLS). On the other hand, geometric accuracy is the closeness of point clouds to true or ground-truth measurements. It is described by Root Mean Square Error (RMSE) which is defined in the equation below. Where \((V)\) is the difference between a measured value on 3D models to its ground-truth value and \((n)\) is the number of measurements[11].

\[
RMSE = \pm \sqrt{\frac{\sum_{i=1}^{n} V_i^2}{n}}
\] (1)

Random distances surveyed by total station (figure 5), were used as ground-truth to assess and compare the geometric accuracy of CRP and TLS point clouds which is sorted out in table 2. RMS errors demonstrate how the two approaches are convergent in term of geometric accuracy.

| Distance (m) | TS | CRP | TLS | CRP | TLS |
|--------------|----|-----|-----|-----|-----|
| 0.360        | 0.360 | 0.357 | 0.000 | 0.003 |
| 0.518        | 0.518 | 0.521 | 0.000 | 0.004 |
| 0.709        | 0.709 | 0.711 | 0.000 | 0.002 |
| 1.116        | 1.117 | 1.123 | 0.001 | 0.007 |
| 2.264        | 2.265 | 2.276 | 0.001 | 0.012 |

Table 2. RMSE of CRP and TLS models referenced to TS measurements.
Figure 5. Measured distances to evaluate the accuracy delivered from TLS technique.

5.3 Cloud to cloud comparison
The resultant point clouds from each sensor have been brought into a quantitative and qualitative comparison with respect to completeness, data voids, density and roughness. The open sources software CloudCompare (CC) has hosted most of the cloud-to-cloud analyses.

5.3.1 Completeness and data voids
Data voids (or gaps) can occur in terrestrial laser scans for a number of reasons including non-portability (rigidity) of scanners, range limitations, obstacles and surface complexity [12]. Likewise, image-derived point clouds may inherent in data voids due to shooting-related issues (poor illumination, lack of overlapping, motion blur, GSD …etc.) or processing related issues.
Detecting incompleteness of point clouds needs more than just visual interpretation, thus cloud to cloud distances have been computed in CloudCompare which implements what is called Multiscale Model to Model Cloud Comparison (M3C2) for direct point cloud comparison in 3D environments. The M3C2 algorithm was designed by [13] for accurate orthogonal distance measurement between two point clouds. The algorithm does not compute a difference in the absence of an intersection with the compared cloud along the normal direction. The method is thus extremely robust for missing data and greatly simplifies the treatment of point cloud as no manual trimming is needed prior to difference computation [13]. Co-alignment between the different datasets is a necessary operation before running the M3C2 algorithm. (Figure 6) shows the cloud-to-cloud distances where the green areas indicate to minor or zero discrepancies and the grey areas are data voids in laser scanning. Furthermore, figure 7 demonstrates the non-normal (or Gaussian) distribution of M3C2 distance with 0.02 m standard deviation.

5.3.2 Point density comparison. Point density is defined as the number of points per unit which is mainly determined by the scanner resolution, the average distance between the 3D coordinates in a point cloud and the scanning geometry [10]. Point density has been computed in terms of the number of neighbours (NoN) as demonstrated in figure 8. It is obvious how photogrammetric approaches produced denser coverage than terrestrial laser scanning, because:

1. TLS recorded more than 40 million points out of 9 scans. However, segmenting the area of interest to get rid of features in the background and cleaning pre-processing have resulted in a massive reduction of laser datasets as can be seen in figure 8.
2. CRP was more concentrated to capture the area of interest, which led to derive minimal mounts of points for the background scene.

5.3.3. Points roughness comparison. Roughness is another important factor for some analysis processes like estimating complexity degree or analysing the physical properties of surfaces [13]. Moreover, roughness gives an indication of point clouds to be implemented in further modelling steps. CloudCompare presents a simple tool to compute roughness which only asks for the radius of a sphere centred for individual points. Resultant roughness, shown in figure 9, is the distance between this point and the best fitting plane computed to its nearest neighbours [14]. It is found that TLS datasets have a higher level of roughness (0.4 mm in average) than that of CRP point cloud (0.03 mm on average). As a result, modelling (meshing) laser point cloud would need more efforts than photogrammetric point cloud, which could have a negative impact on the level of details (LOD) derived from TLS.
6. Discussions and conclusions

In this paper, Terrestrial Laser scanner (STONEX X300) and a DSLR camera (Canon 7D) were tested to document a precious artefact, Lady of Hatra. The impacting factors, settings, and strategies were addressed in depth to reveal the potentiality of each technique in heritage conservation. We have reaped the benefits of merging photography skills with a decent photogrammetric solution (RealityCapture) to derive accurate, consistent and dense point cloud. Additionally, Terrestrial laser scanner (STONEX X300) was also used to deliver 3D point cloud and particular attention was given to measure the quality of registration due to its degree of criticality to reach the final deliverables.

The qualitative and quantitative comparison outlined the feasibility of both techniques to generate 3D digital archives of artefacts with complex details. Thus, the laser point cloud has guaranteed a few millimetres deviations from that obtained out of photogrammetry. However, TLS was more generic (inclusive) to capture all the entire scene while CRP was more targeted to capture the area of interest (LoH). As a result, segmenting point clouds to isolate the artefact led to a massive loss in laser datasets. Moreover, the photogrammetric point cloud is cleaner and smoother which promises easier and faster modelling/meshing operations.

The level of automation, addressed in the comparative analysis, consolidates CRP versus TLS trade-off in terms of time, accuracy, density, methodology and ease to use. As a rule of thumb, STONEX X300 is a mid-range scanner dedicated for large-scale projects which would be labour-intensive and time-consuming to be done with CRP. Therefore, fusing laser scans and digital images is of great benefit for heritage documentation where the laser scanning data provides generic coverage and the imagery complements the datasets to fill gaps (voids) and resolve fine details.

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