

RESEARCH ARTICLE

Structure from Motion (SfM) Photogrammetry as Alternative to Laser Scanning for 3D Modelling of Historical Monuments

Omar Al Khalil^{1*}¹Tishreen University, Syria*Corresponding author: Omar Al Khalil: omarmohammedalkhalil@tishreen.edu.sy

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Abstract:

During the past few years, new developments have occurred in the field of 3D photogrammetric modelling of cultural heritage. One of these developments is the expansion of 3D photogrammetric modelling open-source software, such as VisualSfM, and cost-effective licensed software, such as Agisoft Metashape into the practical and affordable world. This type of SfM (Structure from Motion) software offers the world of 3D modelling of cultural heritage a powerful tool for documentation and visualisation. On the other hand, low-cost cameras are now available on the market. These cameras are characterised by high resolution and a good quality lens, which makes them suitable for photogrammetric modelling. This paper reports on the results of the application of a SfM Photogrammetry system in the 3D modelling of Safita Tower, a medieval structure in Safita, north-western Syria. The applied photogrammetric system consists of the Nikon Coolpix P100 10 MP digital camera and the commercial software Agisoft Metashape. The resulted 3D point clouds were compared with an available dense point cloud acquired by a laser scanner. This comparison proved that the low-cost SfM Photogrammetry is an accurate methodology for 3D modelling of historical monuments.

Keywords: Low-cost photogrammetry, Structure from Motion (SfM), 3D modelling, Point clouds, Laser scanning

Introduction

Historical monuments are of particular importance as they represent the memory and history of the countries where they are placed. These monuments should be protected to prevent their deterioration and destruction [1]. The deterioration of these monuments is due to natural disasters and wars. Modern technology can aid in modelling these monuments to protect, preserve them, and for the benefit of professionals and tourists [2]. Modelling method must take into account the complexity of monuments that comes from the shapes and architectural elements and the number of these elements required to create a given monument.

Currently, 3D laser scanning and SfM Photogrammetry are the main techniques used to record the geometry of historical monuments, in the form of textured 3D point cloud [3]. SfM Photogrammetry involves acquiring images from several positions relative to the studied object. An algorithm, such as the scale-invariant feature transform (SIFT) identifies distinctive features appearing upon multiple images and establishes the spatial relationships between the original camera positions in an arbitrary and unscaled coordinate system. Using control points, a bundle adjustment is then applied to extract a sparse set of coordinates to represent the object [4], [5].

SfM Photogrammetry is an important 3D modelling tool due to automated workflows in the new generation of photogrammetric software. These capabilities have significantly helped to reduce the level of knowledge necessary to obtain satisfactory survey results.

New low-cost photogrammetry software based on the SIFT algorithm rapidly expanded to practice due to the advantages of simple automatic processing of image set into a colour dense point cloud, which can be used for 3D modelling [6]. For low-price, this type of software can perform both image alignment, dense 3D point cloud generation, and 3D model reconstruction in a fully automated way. Commercial software packages are better than free or open-source ones in 3D modelling, but these software packages can find a lot of applications that do not require high accuracy [7]. Thus, Commercial software, together with a standard PC and digital camera, represents an SfM Photogrammetry system that can be used to model cultural heritages in a precise way.

On the other hand, laser scanning technology is a very promising solution for many modelling applications. Laser scanners allow acquiring very quickly a huge amount of 3D point cloud which can be often combined with colour high-resolution digital images [8]. Currently, 3D Laser scanners are widely adopted for 3D modelling of historical monuments.

Each technique owns its advantages and disadvantages at different working fields and depending on the own object's features. Even in many cases, a combination of both techniques can do a more precise and detailed architectural survey of historical monuments [9], [10].

The choice of the most appropriate technique depends on the object to be modelled and on the available budget [11]. Compared to laser scanning, multi-image photogrammetry is cost-effective, and its recent software can provide, dense 3D point clouds just like 3D laser scanners.

In this paper, we deal with SfM photogrammetric 3D modelling of the outside parts of Safita Tower, a medieval structure in Safita, north-western Syria. Our goal is to perform a quantitative analysis of this methodology by comparing it

with an available laser scan. The methodology is outlined in the flowchart in Figure 1.

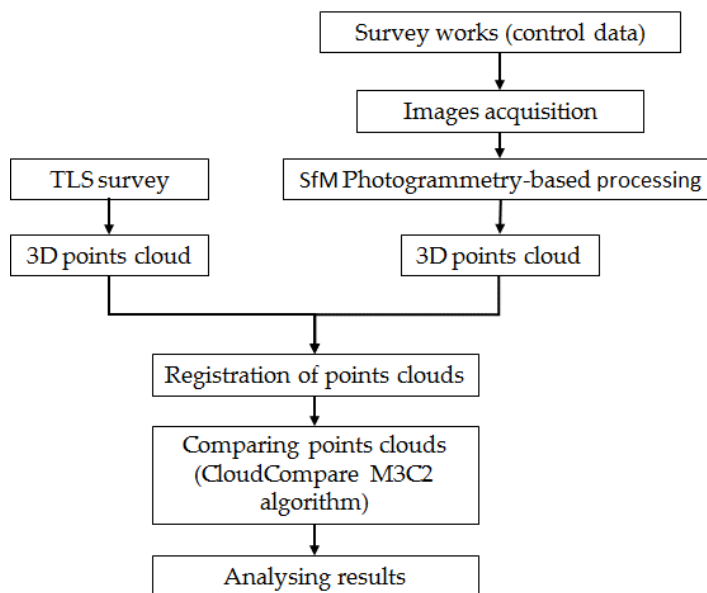


Figure 1. Flow chart of TLS and SfM Photogrammetry data acquisition, processing, and comparing

Results show that it's possible to achieve good geometric accuracy using this technique.

Monument under study

The monument studied in this paper is Safita Tower, a medieval structure in Safita, north-western Syria. It was built during the Crusades upon prior fortifications. The Tower visible today is the remaining keep of the original castle. It has a height of 28 meters, a width of 18 meters, and a length of 31 meters.

The Tower had to be restored in 1170 and 1202 following damages due to earthquakes. The keep in its current shape probably dates from the reconstruction after 1202. It served both as a chapel and a fortress [12]. The exterior part of the Tower consists of four façades (Figure 2).

As for the interior part, it consists of a ground floor that contains a chapel, dedicated to St. Michael (Figure 3 (a)) and a second floor served as a dormitory, and contains many small angled windows that were used by archers to defend the Tower. This floor is called the great hall (Figure 3 (b)).



Figure 2. Western façade of the Tower

There are many cracks in the walls and the ceiling of the church and the hall, as well as in the external façades. These cracks are most likely caused by earthquakes.

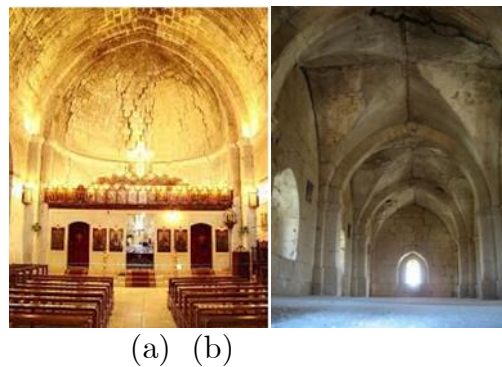


Figure 3. The interior part of the Tower: (a) the church of the Tower (b) the great hall.

Survey methodology

As mentioned above, the Tower suffers from cracks in its various parts. An evaluation of the constructional situation of the Tower was then necessary before undertaking any restoration or reinforcement works. This study requires a 3D detailed model of the Tower to document its current situation. Multi-image automated photogrammetry offers the possibility of obtaining dense 3D point clouds of objects in a rapid, accurate, reliable, flexible, and economical way [13]. This makes it an ideal tool for this field of application.

Control data acquisition

Survey works were carried out for obtaining the control points for the photogrammetric surveying. A traverse was defined by 8 stations in the exterior of the Tower (Figure 4). The least-square adjustment was applied to obtain final station coordinates in a local coordinate system.

Control points were measured on all façades of the Tower. More than 75 control points were measured with a South total station laser measurement. These points were natural points selected in the field. Figure 5 shows an example

of these points. The achieved geometric accuracy of these control points was approximately 2 cm.

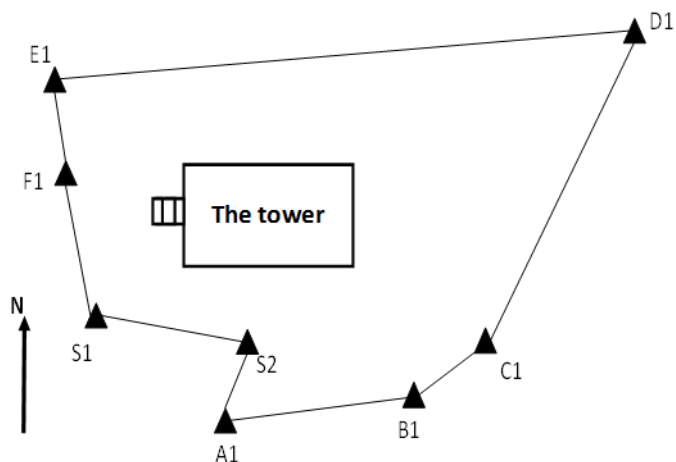


Figure 4. Traverse scheme of the Tower.

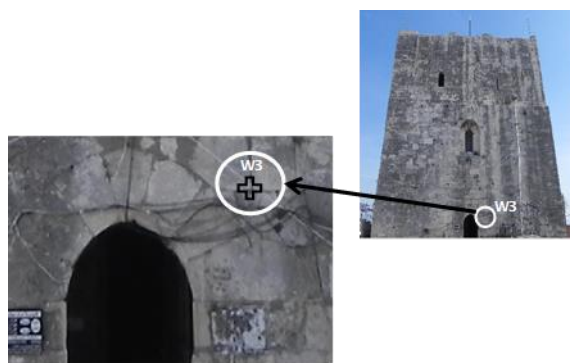


Figure 5. Details of a natural control point.

Camera calibration

Image acquisition was performed by the use of 10.3 MP Nikon Coolpix P100. This camera was carefully pre-calibrated to determine accurate values for the elements of interior orientation [14]. The calibration process was twice performed using PhotoModeler USA 2017, a commercial software [15]. This double calibration was necessary to verify the stability of the camera's parameters. Table 1 shows the calibrated parameters in the calibration process and the differences between the values of these parameters.

Table 1. Double calibration parameters

| Parameter | | Calibration 1 | Calibration 2 | Differences |
|--------------------------------|-------|---------------|---------------|--------------|
| Focal length | | 4.848517 mm | 4.810239 mm | 0.008300 mm |
| Principal point | X_p | 3.150097 mm | 3.148592 mm | 0.001505 mm |
| | Y_p | 2.29729 mm | 2.307135 mm | -0.009845 mm |
| Lens distortions parameters | K_1 | 8.29E-04 | 9.01E-04 | 0.000072 |
| | K_2 | 4.93E-05 | 4.20E-05 | 0.000007 |
| | P_1 | 3.48E-04 | 3.37E-04 | 0.000011 |
| RMS of the calibration process | | 0.2 pixels | 0.2 pixels | |

Differences in the previous table show the stability of the parameters calculated from the two calibration processes. The standard deviation of measuring image points during the calibration is less than 1 pixel, and therefore the accuracy criteria for the parameters are achieved.

Images acquisition

Due to the great height of the Tower (28 meters) and the insufficient shooting distances, most photos were taken from the roofs of the surrounding buildings. That was the only possible solution to image the high parts of the Tower. We could not use a crane because of the complex geographic location of the Tower.

Images were taken in maximum resolution as possible (3648x2736 pixel), with good overlapping between images, and the presence of points on as many images as possible. The exterior part of the Tower has been divided into the west, south, north, and east façades. The photos of each façade have been grouped to better control the processing result of the adopted software. Except for the roof, the whole process required 105 photographs for the west façade, 155 for the north façade, 73 for the east façade and 99 for the south façade.

Results and discussion

SfM photogrammetry

In our research, the software Agisoft Metashape, produced by the Russian company Agisoft LLC, was used to create 3D products of the studied monument (Safita tower). At the first stage, the software reconstructs the virtual positions of the cameras that were used. The next stage is building geometry. This step involves the creation of a 3D dense point cloud and a 3D polygon mesh, representing the object surface. This model is also known as a Digital Surface Model (DSM). To complete the georeferencing task, Agisoft requires some control points that can be used to scale the 3D model and to achieve higher accuracy [16]. After the geometry (i.e. the mesh) is constructed, it can be textured and/or used for orthophoto generation.

The previous steps have been implemented for each façade of Tower to obtain sparse clouds (to achieve the relative orientation), 3D dense point clouds and 3D models. To calculate the absolute orientation of images, all available control points were measured manually on the images of each façade.

To assess the geometric accuracy of the orientation, Agisoft Metashape recalculates all the control points as checkpoints. Table 2, shows the geometric accuracy based on the measurement of re-projected control points.

Table 2. Geometric accuracy based on the measurement of reprojected control points

| Façade > | West | South | East | North |
|-------------------------|-------|-------|-------|--------|
| Points of spare cloud | 89000 | 90000 | 39800 | 119000 |
| Measured control points | 33 | 17 | 14 | 13 |
| σ_x (cm) | 1.4 | 1.8 | 1.3 | 2.4 |
| σ_y (cm) | 1.3 | 1.1 | 1.4 | 1.3 |
| σ_z (cm) | 1.2 | 1.0 | 1.1 | 1.0 |
| σ_{Total} (cm) | 2.6 | 2.3 | 2.2 | 2.9 |

The results for all façades are good because they are too close to the accuracy of the control points measured on these façades.

The following is an example of the processing results for the western or main façade of the Tower. First of all, the images were relatively oriented using more than 89300 tie points (Figure 5). Then the control points were used to determine the position and orientation of the cameras in the adopted local coordinate system (Figure 6). Using the images oriented in the previous stage, a dense 3D point cloud was generated (Figure 6 (a)) at a higher processing level, so we obtained approximately 14 million 3D points on this façade. From the previous dense cloud, a surface model (Figure 7 (b)) was generated, so we obtained a TIN with more than 1900000 triangles. Then a 3D photo-realist model (Figure 7 (d)) was generated by re-projecting the images on the surfaces of the surface model resulting from the previous step. Finally, an orthophoto was generated for this façade (Figure 7 (c)). The ground sampling distance (GSD) of this orthophoto is 3.67 mm.

The same processing steps were applied for the rest of the Tower façades, so we obtained the results shown in Table 3.

Table 3. Processing results of the façades of the Tower

| Façade | Number of photos | Spare cloud | TIN faces | GSD |
|--------|------------------|-------------|-----------|------|
| South | 103 | 90421 | 19377202 | 4.45 |
| East | 73 | 39722 | 9359419 | 4.77 |
| North | 157 | 118824 | 22429635 | 3.80 |

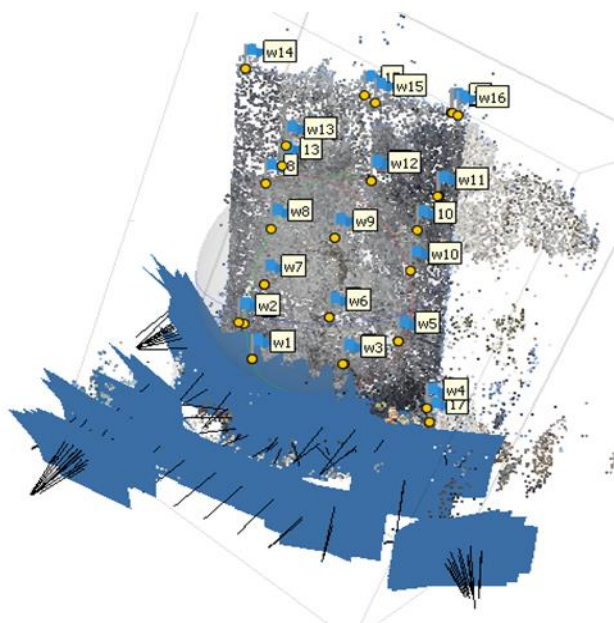


Figure 6. Sparse cloud and camera locations.

Since the control points, sparse clouds, 3D dense point clouds, 3D surface, and photo-realist models of different façades are in the same reference system, it was possible to merge them to obtain the overall 3D products of the Tower. According to the processing report generated by the software, the overall modelling geometric accuracy of the Tower reached 2.26 cm. On the other hand, the total number of images needed to cover all parts of the Tower was 432, and the number of dense clouds points of the whole Tower reached 65 million. As for the number of faces (triangles) of the 3D surface model, it reached 8.8 million faces. Figure 8 shows the main 3D products of the Tower.

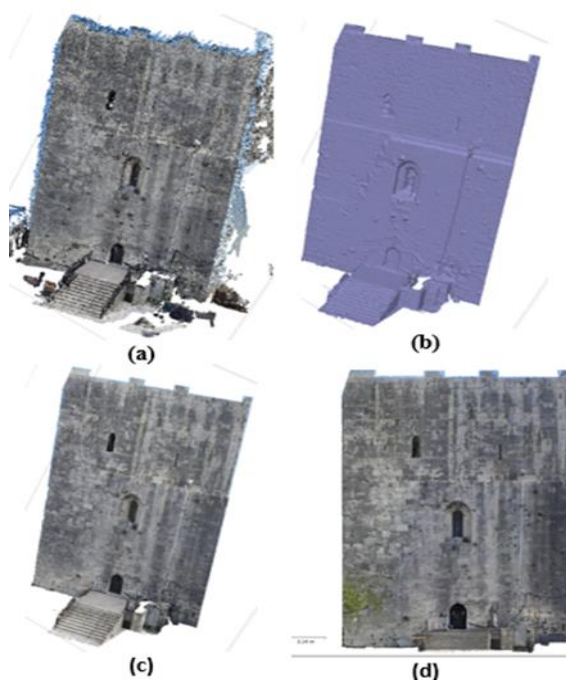


Figure 7. 3D products of the western façade: (a) dense cloud, (b) surface model, (c) photorealistic model, (d) orthophoto

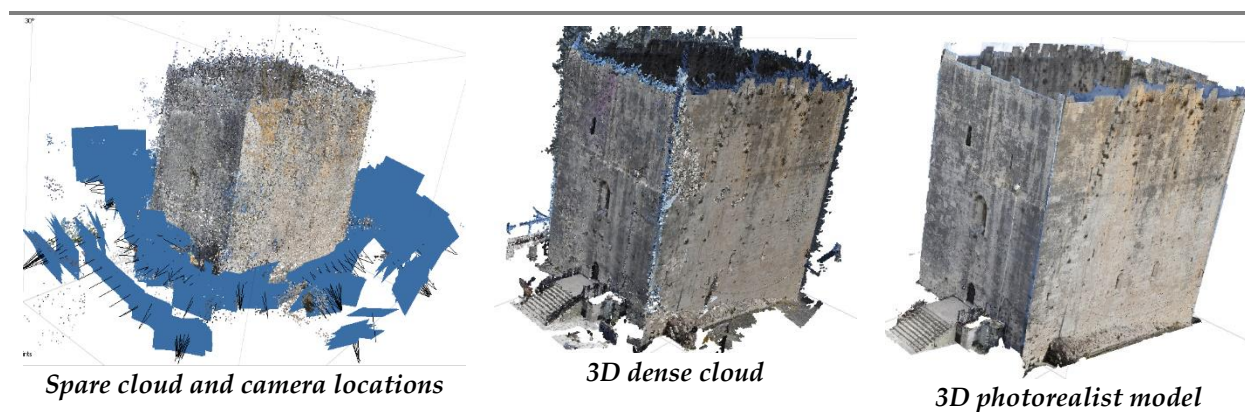


Figure 8. 3D products of the Tower.

Laser scanning

3D point clouds of the exterior parts of the Tower are available. This cloud was reconstructed using a Focus3D laser scanner, manufactured by FARO by Lebanon company (3DExperts) in 2019 (Figure 9). This scanner features a full 360° x 305° field-of-view, with high scan speed (976k pts/sec) and the distance measurement is realised by the phase-shift measurement principle [17]. Each scan has automatically recorded millions of points. 3D laser scanning data processing utilised the software SCENE version 8.0. SCENE is a software specifically designed to process 3D point clouds collected by FARO® FocusS, Focus3D, and Freestyle3D Laser Scanners. SCENE processes and manages scanned data easily and efficiently by using automatic object recognition as well as scan registration and positioning. SCENE can also generate high-quality colorised scans. The available laser scanning suffers from the following problems:

- It does not exist in the same spatial reference as that generated by photogrammetry.
- The 3D point cloud is available only in (rcp) format (compatible with AutoCAD or Revit). This format cannot be handled by CloudCompare software (used to compare the point clouds).

To overcome these problems, the following solution was implemented:

- To represent the SfM clouds in the same coordinate system of the TLS cloud, the latter was exported to Civil 3D, and the 9 GCPs control points were then measured on the different parts of this cloud.
- Using the previous GCPs, the SfM clouds were reoriented in Agisoft Metashape, and thus became in the same spatial reference of the TLS cloud. To evaluate the accuracy of the TLS cloud to SfM cloud registration, the 9 control points were recalculated by Agisoft Metashape as checkpoints (Table 4).

Table 4. The residuals of the measured CPs on TLS cloud after being considered as checkpoints by the software

| Point | Façade | σ_x (cm) | σ_y (cm) | σ_z (cm) | σ_{Total} (cm) |
|-------|--------|-----------------|-----------------|-----------------|-----------------------|
| 1 | South | -4.9 | -3.3 | -4.1 | 7.2 |
| 2 | West | 4.6 | 1.9 | 3.2 | 5.9 |
| 3 | West | -3.3 | -2.9 | 3.6 | 5.7 |
| 4 | South | -4.2 | 3.6 | 0.6 | 5.6 |
| 5 | North | -1.1 | 5.3 | 0.2 | 5.4 |
| 6 | East | 0.8 | -2.7 | 2.8 | 4.0 |
| 7 | West | -2.2 | 0.2 | -2.9 | 3.7 |
| 8 | West | 2.7 | 0.4 | -1.7 | 3.3 |
| 9 | West | -1.7 | -1.9 | -0.5 | 2.7 |

The main square errors along the axis were calculated: $\sigma_x=3.2$ cm, $\sigma_y=2.9$ cm, $\sigma_z=2.6$ cm, which yields an overall square error, $\sigma_{total}=5.0$ cm. This high value can be justified by the difficulty of measuring some control points on the TLS cloud.

- SfM clouds were then exported in the (*.ply) format, which holds geometrical information along with RGB data and 3D normal data (nx, ny, nz). This is read and managed in CloudCompare.

- On the other hand, the TLS cloud was imported to the free software Autodesk ReCap 360 and then exported in the format (*.pts), read, and managed in CloudCompare.

Since the SfM and TLS clouds have been framed in the same reference system, comparison of point clouds was then possible. Comparisons between point clouds representing the different surveys were carried out using Cloud Compare GPL software, using the M3C2 algorithm.

The overall RMS (Root Mean Square) values along the axis were calculated: RMS along the X-axis (3.2 cm), RMS along the Y-axis (2.9 cm), RMS along the Z-axis (2.6 cm) and overall RMS (5.0 cm). This high value can be justified by the difficulty of measuring some control points on the TLS cloud.

- SfM clouds were then exported in the (*.ply) format, which holds geometrical information along with RGB data and 3D normal data (nx, ny, nz). This is read and managed in CloudCompare.

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Figure 9. 3D laser scanning of the Tower.

Comparing SfM clouds with TLS clouds

For each façade, the point clouds, one corresponding to the SfM point cloud, and the other corresponding to the TLS survey were imported into CloudCompare (V2). The precision of each surveying technique was determined by calculating the linear distance between the point clouds in CloudCompare with the Multi-scale Model-to-Model Cloud Comparison (M3C2) algorithm. This algorithm works directly on raw point clouds, with no meshing or gridding [18], and is split into two main steps:

- 1- estimation of surface normal orientation at a scale consistent with the local surface roughness.
- 2- quantification of the mean cloud-to-cloud distance (i.e. surface change) along the normal direction.

When applying this algorithm, the projection of the core points is done keeping original positions; in this way, a new cloud is generated, containing the differences between the tested point clouds [19].

Regarding the western façade, when using the TLS point cloud of the west façade (30.000000 points) as a reference (Figure 10), the mean absolute difference is 2.2 cm while the 98.75% of the computed differences are lower than 14 cm (Figure 11). The higher differences are observed in the area of the stairs leading to the entrance to the Tower. This is because of fewer camera stations locate in this area. Some high differences are detected in the upper parts of the façade. This is due to the difficulty of photographing these parts. As for the eastern façade, a TLS point cloud of the east façade (14200000 points) was used as a reference (Figure 12) and the mean absolute difference is 0.06 cm while 97.73% of the computed differences are lower than 1 cm (Figure 13). We note that there is an almost perfect match between the two clouds, thanks to the large number of images covering this façade and the ability to image the upper parts of this façade.

Concerning the southern façade, when using the TLS point cloud of the south façade (25500000 points) as a reference (Figure 14), the mean absolute difference is 3.7 cm while 98.97% of the computed differences are lower than 8 cm (Figure 15). High differences are observed in the upper parts of the façade. Just like the

case of the western façade, this is due to the difficulty of photographing these parts.

Finally, the TLS point cloud of the north façade (47700000 points) was used as a reference (Figure 16). In this case, the mean absolute difference is 4.9 cm while 94.54% of the computed differences are lower than 14.7 cm (Figure 17). High differences are observed in the lower and upper parts of the façade, due to the difficulty of photographing these parts. Some of the lowest parts of the façade are obscured due to the presence of a nearby restaurant.

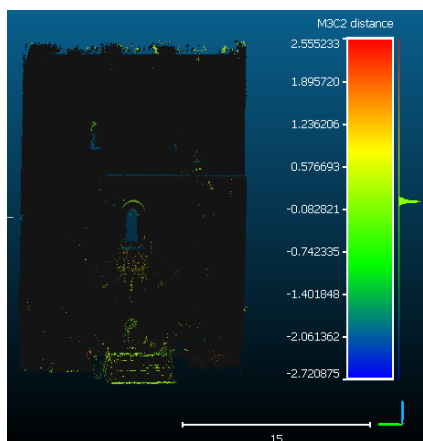


Figure 10. Western façade: the difference between SfM and TLS point clouds setting the TLS dataset as reference.

Gauss: mean = 0.022185 / std.dev. = 0.124766 [1367 classes]

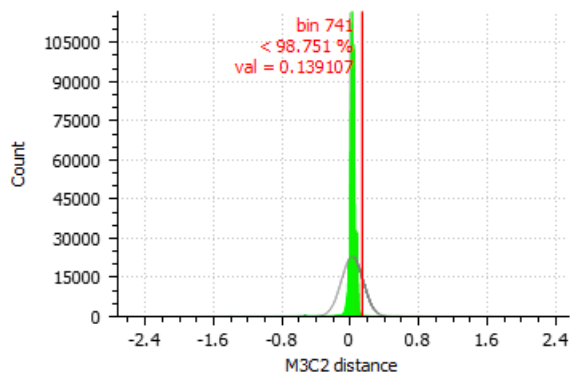


Figure 11. Histograms of the differences between SfM and TLS point clouds for the western façade setting the TLS dataset as reference.

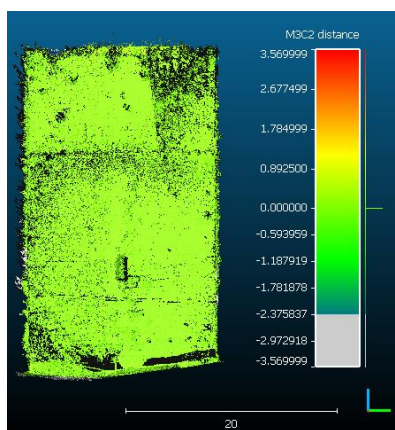


Figure 12. Eastern façade: the difference between SfM and TLS point clouds setting the TLS dataset as reference.

Gauss: mean = 0.000564 / std.dev. = 0.127478 [877 classes]

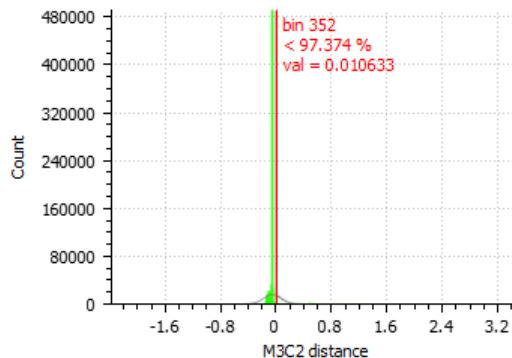


Figure 13. Histograms of the differences between SfM and TLS point clouds for the eastern façade setting the TLS dataset as reference.

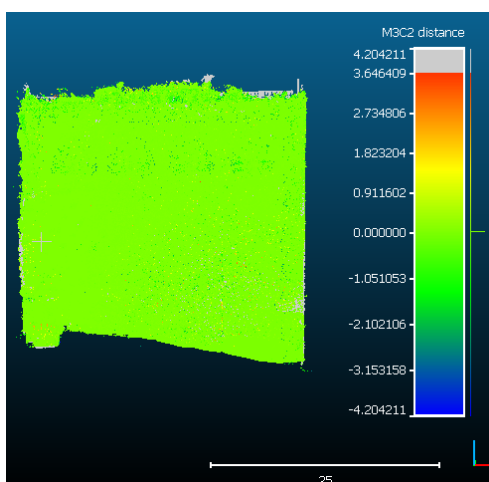


Figure 14. Northwestern façade: the difference between SfM and TLS point clouds setting the TLS dataset as reference.

M3C2 distance (850939 values) [256 classes]

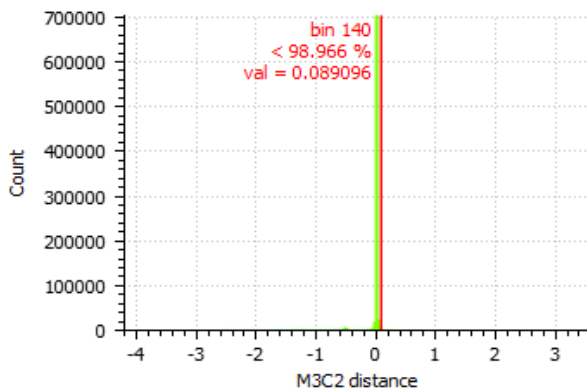


Figure 15. Histograms of the differences between SfM and TLS point clouds for the north-western façade setting the TLS dataset as reference.

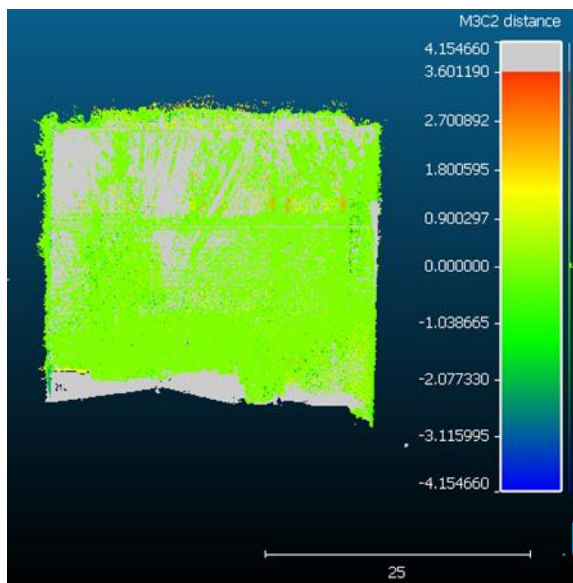


Figure 16. Northern façade: the difference between SfM and TLS point clouds setting the TLS dataset as reference

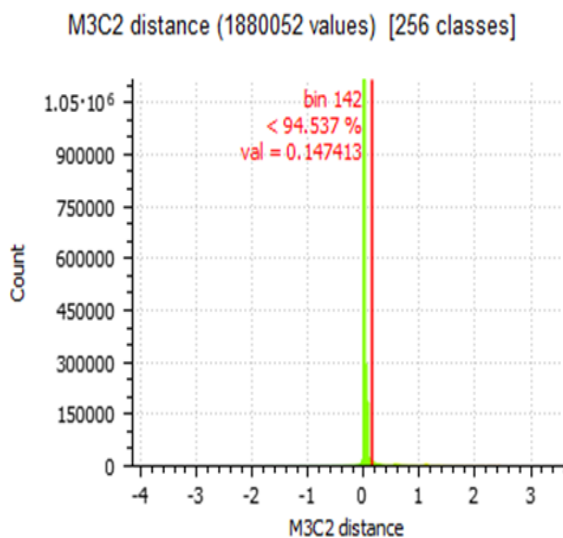


Figure 17. Histograms of the differences between SfM and TLS point clouds for the northern façade setting the TLS dataset as reference.

Vectorisation of 3D clouds

To obtain the 3D vector model from the TLS point cloud, the cloud is usually exported to software such as Civil 3D and Revit, where the vectorisation tools (point, polyline, polygon, etc.) available in this software are used (Figure 18). This process is long and requires special skills, in addition to the high cost of the software.

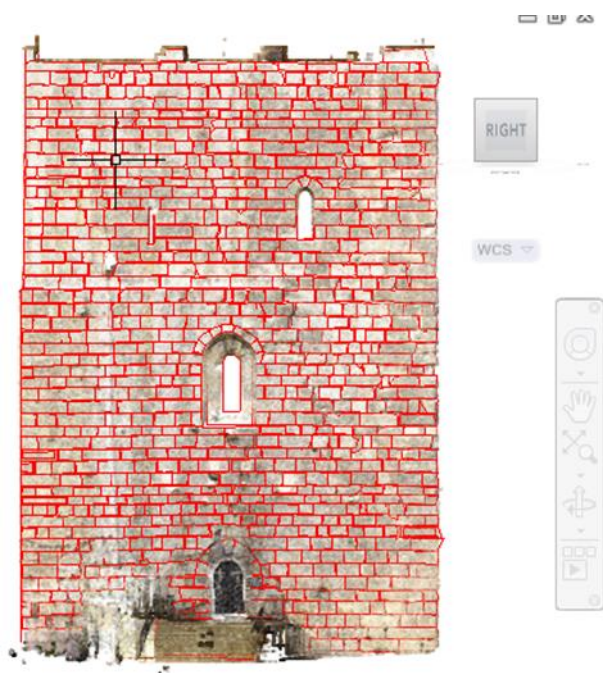
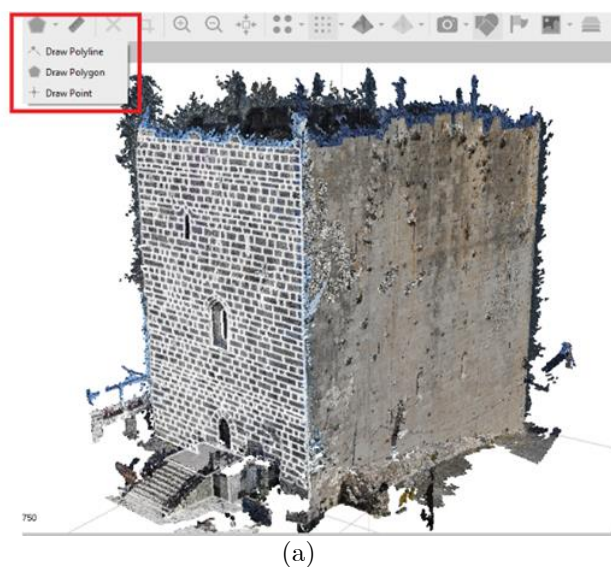


Figure 18. Vectorisation of TLS point cloud in Civil 3D.

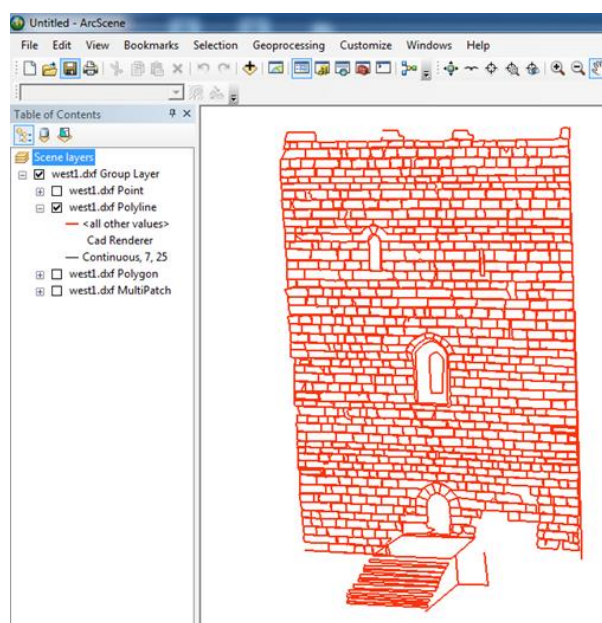
In contrast, some SfM Photogrammetry software own simple tools for direct vectorisation on the 3D point cloud (point, polyline, polygon) (Figure 19 (a)). As examples of this kind of software we mention, 3DF Zephyr, Pix4D, and Agisoft Metashpe (the software used in our research). The vectorisation process inside SfM software is relatively simple, compared to Civil 3D and Revit, in addition to the ability to automate some measurements (3DF Zephyr for example).

Finally, we note that vectorisation results can be exported in well-known graphical formats such as *.dxf and *.shp format. This means that it can be later exported to other software for further processing (Figure 19 (b)).

Mostly, there are tendencies to develop moor cloud vectorisation tools within SfM software, and this will be proven by upcoming versions of the software.



(a)



(b)

Figure 19. (a) Tools for vectorisation of SfM point cloud within Agisoft Metashape (b) vectorisation results of the western façade displayed in ArcScene.

Conclusion and further works

Many historical monuments in Syria are left undocumented, which prevents their preservation and restoration in case of damage. While 3D laser scanning and SfM Photogrammetry are the most suitable techniques for 3D documentation of such monuments. SfM Photogrammetry is low-cost because it utilizes low-cost digital cameras, while a 3D laser scanner requires its specialised expensive equipment. On the other hand, some of the SfM Photogrammetry software is freely available and some others are low-cost, while a 3D laser scanner requires software that can handle data captured by the scanner. Finally, the outputs of SfM Photogrammetry are the same as 3D laser scanner products (3D point clouds, 3D models, etc.) and almost have the same accuracy.

In this paper, a low-cost SfM Photogrammetry system (everyday digital camera, low-cost processing software, and standard PC), was used to obtain all necessary products for 3D documentation of Safita Tower. The reached accuracy of 3D modelling was 2.26 cm and it can be considered as good accuracy. We should be able to improve this accuracy by using a drone. The drone should help in better imaging the upperparts and the roof (which was not modelled) of the Tower.

On the other hand, comparison results of laser scanning point clouds with photogrammetric point clouds indicated that the SfM Photogrammetry could be considered as a precise alternative or complementary to laser scanning.

Acutely we are working on the 3D modelling of the interior parts of the Tower (the church and the great hall) to obtain a complete 3D model of this Tower. The complete 3D point cloud will be then processed to develop an HBIM of this monument.

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