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PHOTOGRAMMETRIC MEASUREMENT OF A WOODEN TRUSS

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Abstract

Wooden trusses are a very specific object for measurement. They are often very complex and hard to reach; they are characterized by narrow spaces and low-lighting conditions. In recent years, laser scanning technology was mostly used for this task, because of its contactless nature, the possibility of measurement in the dark, and the robustness of the resulting 3D point clouds. Photogrammetry was mostly used in special cases, e.g., for the measurement of a few selected truss components, but not for the 3D modelling of an entire truss. However, the progress in computer vision algorithms is allowing us to accomplish image-based-modelling on very complex objects. The following contribution compares the point clouds of a wooden truss generated by the leading photogrammetry systems with a point cloud from laser scanning. The results confirm the interesting potential of actual photogrammetric methods in the modelling of complex objects such as wooden trusses.

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Key words

- Photogrammetry,
- Structure from motion,
- Laser scanning,
- Wooden truss,
- Point cloud,
- Cultural heritage.

1 INTRODUCTION

The possibilities inherent in today's automation of image processing in computer vision allow us to create 3D models of various objects faster and easier than ever before. In recent years, various photogrammetric systems have been created and enhanced that can also be used by non-photogrammetric experts; a significant number of applications have been found in nearly every area of the economy (Trhan, 2017). These systems are relatively easy to handle and capable of processing images from various types of cameras and sensors. They work on similar principles and use the natural surface texture of the object modelled to detect features recognizable in the neighboring images. These corresponding features help to determine the relative position and orientation of camera stations in a reconstructed scene and, in most cases, also help to calibrate the camera in order to solve the interior orientation parameters. After such automatic or semi-automatic reconstruction of a scene, it is possible to georeference a 3D scene based on Ground Control Points (GCPs) and create very detailed 3D point clouds and models. However, the 3D models do not need to serve as the final product. In special cases they can just help solve the required task, e.g., create a base for the generation of orthophotomosaics, which can be easily vectorized in CAD systems.

Even though the mentioned systems should produce similar results, they do not. Each one has its own strengths and weaknesses; some produce more detailed models than others; some can process the images faster; some cannot automatically orient all the images in the same scene and need bigger overlaps between them. Free and commercial solutions, e.g., user-friendly one-click "black boxes" or professional systems with the option of changing various settings, exist. The user should always know the capabilities of the software used if he wants to achieve the results required. This is also the main goal of this contribution, i.e., to show and compare the results from various photogrammetric systems in a special application, which the measurement of wooden trusses surely is.

2 MEASUREMENT OF WOODEN STRUCTURES

There are several methods that can be used for the measurement of a wooden truss. Nowadays laser scanning technology is mostly used, but we can also use photogrammetry or, in simple cases, the standard geodetic measurement of selected points (the spatial polar method using a total station) or just measuring the lengths by a tape or a laser range-finder. The appropriate method should be selected based on the purpose of the final results. The measurements can serve as a basis for the documentation of the truss before its reconstruction, the creation of Building Information Models (BIM), or structural analysis. In special cases, it is possible to measure the deformations of selected wooden components. There is also the possibility of combining all of the above-mentioned methods, especially in the complexity of the BIM area, where there is a need for generative processes without losing information (Banfi et al., 2017).

The main advantages of laser scanning are the fact that it can operate regardless of lighting levels and that it can produce a great number of points for the definition of the geometry of a structure without defining the elements to survey beforehand (Balletti et al., 2003). Actually, tests proved that recorded laser intensity values bring better results in night-time measurements (Voegtle et al., 2008). Thanks to its contactless nature and range, it is also safe to use laser scanning in complicated and dangerous environments. Timber structures are very specific, especially in historical buildings, because of the irregularities of the individual components. Point clouds from laser scanning contain a great amount of information about the shape of truss components, so advantage should be taken of its rapidity of acquisition and its richness of details with the aim of avoiding the traditional simplified 2D layouts (Guzzetti et al., 2013). There are many works promoting the usability of terrestrial laser scanning (TLS) in the measurement of timber structures. Interesting applications have been presented, e.g., by (Bertolini et al., 2015), (Lee et al., 2015) or (Perria et al., 2017).

On the other hand, the use of photogrammetry can be much cheaper (a professional DSLR camera is less expensive than a TLS instrument) and provides not only 3D documentation of the object measured, but also high resolution textural information which can help to analyze the state of the timber truss members. Photogrammetric measurement is always separated into two steps: 1. acquiring data (taking images) and 2. processing (interior, relative and absolute orientation and 3D modelling). The small amount of time needed for the terrain work is one of the many advantages of photogrammetry. Moreover, it is possible to easily get the camera to locations which are not possible for TLS.

The main problems in the use of photogrammetry for the measurement of timber truss structures are the bad illumination conditions and the complexity of the structures, which create a need for more images and involve time-consuming processing. The use of a total station for GCP measurement is also necessary.

There are significantly fewer examples of photogrammetric truss measurements in comparison to laser scanning and, despite the state of automated image processing today, the majority of them include the manual measurement of image coordinates.

Multi-image convergent photogrammetry was used in (Lubowiecka et al., 2007) to create a 3D model of a timber structure for structural analysis. All the points of the model were measured manually using PhotoModeler software.

(Koehl et al., 2015) used a combination of TLS and photogrammetry to create a 3D model of a historical building in France. Photogrammetry was mainly used for the modelling of the exterior facades, but it was also tested on the timber frame structure. The corresponding points were again measured manually.

Examples of the usability of automated image-based modelling of wooden trusses are mentioned by (Marčiš et al., 2016). The point clouds and meshes generated were used for the creation of orthophotomosaics and the documentation of various historical buildings through 2D layouts. Photogrammetry was used as the main method without a need for TLS.

Because of the great results that laser scanning brings to truss measurement, it is logical that the use of computer vision techniques in this area is less common. There is often a combination of TLS and photogrammetry used, but photogrammetry is almost always only employed for the measurement of the exterior parts and rooftops of buildings, e.g., with the support of an Unmanned Aerial Vehicle (UAV) (Meschini et al., 2014). However, the performance of the leading photogrammetric systems shows that they are also capable of modelling very complex objects, such as insects, in great detail. (Nguyen et al., 2014).

In the past, many evaluations have been done of various photogrammetric solutions, i.e., either analyzing only one selected system (Koutsoudis et al., 2014), comparing its results to TLS (Fassi et al., 2013), or comparing various photogrammetric systems on different data sets (Nikolov & Madsen, 2016). Benchmark scenarios were created for Dense Image Matching (DIM) testing of algorithms (Nex et al., 2015), but no comparison was done for a timber truss structure. For these particular reasons, we decided to analyze the results from today's leading photogrammetric systems and compare them with TLS on the same object, i.e., a historical wooden truss.

3 DATA COLLECTION

The object of measurement presented in this paper is located in the complex of an old hospital in Topoľčany in Slovakia that serves today as the Microbiology pavilion (Fig. 1).

The footprint of the building creates the letter "L". The timber truss used for the testing is separated in two parts that are connected through the main staircase in the middle of the building (Fig. 2 on the left).

3.1 Reference data – laser scanning

The whole truss structure was scanned using a Trimble TX5 scanner. A total of 17 scans with scanning steps set up to 3 mm / 10 m were conducted. Registration (alignment) of the individual scans was done with the Autodesk ReCap software.

Fig. 1 *Microbiology pavilion of the old hospital in Topoľčany.*

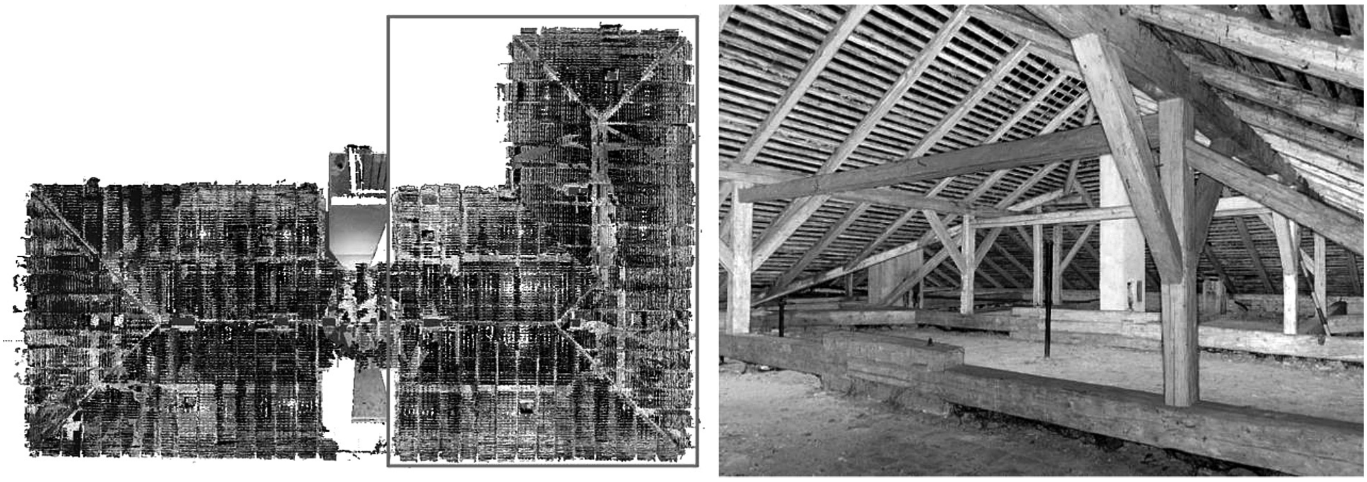

Fig. 2 *Timber truss of the Microbiology pavilion separated in two parts by a staircase (left) and an inside look at the selected part of the truss (right).*

Photogrammetry was only used for the L half of the truss (Fig. 2 – selection of rectangle); it contained 10 laser scans with 38 million points. The dimensions of this selected part of the truss structure are 20 x 14 x 4 m. The registration results of the scans are listed in Tab. 1.

Tab. 1 *Laser scan registration results from Autodesk ReCap*

Scan No.	Overlap (%)	Accuracy <6mm (%)	Balance
1	44.29	99.83	0.4041
2	19.31	98.71	0.6331
3	18.37	98.67	0.4902
4	22.28	98.96	0.5554
5	28.62	98.98	0.6191
6	26.71	98.82	0.6429
7	11.30	99.44	0.6852
8	18.44	99.33	0.5488
9	10.34	99.14	0.3709
10	8.23	100.00	0.3434

The overlap represents the percentage of points which lie in the same region as the points from other scans. The degree of accuracy is represented by the percentage of points which are closer than 6 mm to the points of the same region but from other scans. The balance describes how strong the scans aligned to each other are in all 3 coordinate axis directions, and it can achieve values from 0 to 1, the higher the better.

3.2 Photogrammetric data

Two hundred thirteen images were taken using a 36-megapixel Nikon D800E DSLR camera with a Nikkor AF 20mm lens with flash support. The overlap between the neighboring images reached approximately 60-80%, depending on the circumstances, and there were also many images of the flat roofing with the aim of interconnecting the opposite sides of the truss structure through image strips (Fig. 3).

There were no GCPs measured by a total station; it was assumed that the results from laser scanning and photogrammetry would be aligned with sufficient accuracy either manually, based on the characteristic points selected from the TLS point cloud (edges etc.), or automatically, depending on the photogrammetric software.

Fig. 3 *Camera positions inside the truss structure (left) and an image taken by the DSLR camera (right).*

4 IMAGE-BASED MODELLING SYSTEMS USED

The photogrammetric systems based on computer vision techniques mostly work with algorithms such as Structure from Motion (SFM), Semi-Global Matching (SGM), Scale Invariant Feature Transform (SIFT) or Random Sample Consensus (RANSAC). This paper is not aimed at fully describing the algorithms mentioned above; the principles of automatic scene reconstruction from images are well described in other literature, e.g., by (Westoby et al., 2012), but a brief summary of individual image-processing steps would be useful. These steps include:

1. Detection of keypoints (features) in the surface texture of the object.
2. Matching – pairing corresponding keypoints on different images.
3. Relative orientation of cameras within a scene.
4. Bundle adjustment – adjusting the parameters of the interior and the relative orientation (resulting in a sparse point cloud of tie points).
5. Georeferencing - measuring GCPs or adding information about the scale, i.e., solving the absolute orientation with the possible adjustment of the interior and exterior orientation parameters based on GCPs.
6. Computation of dense clouds – based on multi-view stereo (MVS) or pair-wise stereo image matching techniques.
7. Computation of final triangulated irregular network (TIN) or mesh.
8. Export of products (orthophotomosaics, Digital Elevation Models (DEM), contours, profiles etc.).

There are many photogrammetric systems nowadays that work on these principles with similar workflow, e.g., Agisoft PhotoScan Professional, Capturing Reality RealityCapture, Bentley ContextCapture, Autodesk ReCap Photo, Eos Systems PhotoModeler UAS, VisualSFM, and many more. We compared the results from these systems from different points of view, i.e., the number of successfully oriented photos, the accuracy of the relative orientation, the overall geometric accuracy of the resulting point cloud, and the surface detail of the components selected. The time needed for computation was not compared due to the different computers used for the processing; that is mostly a question of processor power and the amount of RAM, so it is not comparable, for example, if we use the Autodesk ReCap Photo, which uses an external server for processing. A short overview of the differences between the mentioned software is in Tab. 2.

PhotoScan (www.agisoft.com, 2018) and PhotoModeler (www.photomodeler.com, 2018) software are two of the most commonly used photogrammetric solutions today. The PhotoModeler software has an especially long history of various professional applications; its greatest advantage is its support of more than one photogrammetric method, i.e., it supports not only the automated production of dense point clouds, but also multi-image convergent photogrammetry and videogrammetry with the support of coded targets. PhotoModeler also supports many transformations and various settings. On the other hand, PhotoScan was one of the first user-friendly solutions for automated 3D modelling from images, which also enabled the creation of professional results by non-photogrammetrically educated users.

Some of the systems enable combining photogrammetry directly with laser scanning; however, the functionality of this option is different. RealityCapture (www.capturingreality.com, 2018) enables the alignment of laser scans and photos directly in one project; the whole process works automatically. There is no need for manual measurement of GCPs between the point clouds from both technologies; it generates panoramic images from every scan station, and these images are used to automatically orient these different data sets to each other, while the TLS point clouds serve as a geometric reference. ContextCapture, which is based on Acute3D technology (www.acute3d.com, 2018), also works with data from laser scanning, but it needs GCPs for the photogrammetric part of the processing to merge the TLS and photogrammetrically reconstructed scene in the same reference coordinate system. The same approach is applied in the ReCap Photo by Autodesk (www.autodesk.com, 2018). The 3DF Zephyr Pro has its own solution for aligning laser scans with photogrammetric data, i.e., two or more point clouds can be aligned using the Iterative Closest Point (ICP) function with the possibility of the automated correction of the translation, rotation, and scale of the photogrammetrically generated point cloud relative to the laser scan (www.3dflow.net, 2018). However, the two point clouds have to first be roughly aligned and scaled to use this operation.

From this point of view, RealityCapture has a great advantage on the market because it can easily combine the robustness and geometric accuracy of laser scans with the amount of detail acquired by photogrammetry.

Lastly, VisualSFM works on a GPL license and, if used with Cluster-based Multi-View Stereo (CMVS) or Patch-based Multi-View Stereo (PMVS) software from Yasutaka Furukawa (Furukawa & Ponce, 2010), it shows good results not only in the automated relative image orientation but also in the dense cloud computation (Rusu et al., 2008). It was included in this test as a free solution for scientific purposes.

5 PHOTOGRAMMETRIC PROCESSING

Each software tested has various settings of its own for the individual processing steps. To make the results comparable, similar settings were chosen (Tab. 3). The 213 images were processed in

Tab. 2 *Overview of the photogrammetric systems compared (ordered alphabetically)*

Software	Possibility of online processing	TLS support	Cost (€)
3DF Zephyr Pro	No	Yes	2400
Agisoft PhotoScan Professional	Network processing on more PCs	No	470 edu / 3000 commercial
Autodesk ReCap Photo	Online only	Yes	400 / year – as part of ReCap Pro solution
Bentley ContextCapture	No	Yes	On request
Capturing Reality RealityCapture	No	Yes	99 for 3 month promo / 15,000 perpetual
Eos Systems Inc. PhotoModeler UAS	No	No	170 per month / 3430 permanent
VisualSFM (PMVS)	No	No	General Public License (GPL)

Tab. 3 *Processing settings in the individual systems.*

Software	Alignment settings	Dense cloud settings	Georeferencing method
3DF Zephyr Pro	Presets: Deep	Presets: High	Semi-automatic with TLS
Agisoft PhotoScan Professional	Accuracy: Medium Key point limit: 80 000 Tie point limit: 0	Quality: Medium Filter: Aggressive	Manual measurement of GCPs
Autodesk ReCap Photo	Auto - no options	Auto - no options	-
Bentley ContextCapture	Key point density: High	Geom. precision: High	Manual measurement of GCPs
Capturing Reality RealityCapture	Mode: High Max features per image: 80 000 Detector sensitivity: Ultra	Normal mode	Automatic with TLS
Eos Systems Inc. PhotoModeler UAS	Auto-calibration: On Point density: Medium	DSM from MVS Min. visible images: 2	Manual measurement of GCPs
VisualSFM (PMVS)	Default	PMVS default	Manual measurement of GCPs

all the above-mentioned systems, but not every one of them could orient the whole set of images. Due to these issues, various settings were tested to align the most images possible; the results in Tab. 3 are from the best variants. All the other unlisted settings remained the default settings. To ensure that the conditions were the same for all the systems compared as much as possible, no effort was made to align the remaining images manually; only the reconstructed parts were analyzed.

6 COMPARISON OF IMAGE-BASED MODELLING SYSTEMS

6.1 Integrity of the results

ReCap Photo was tested using an educational license, which is capable of processing only 100 images at a time. Due to this issue, two sets of images with good overlaps were selected (each containing 100 images) for the processing in ReCap Photo. But the results were far from satisfactory – the first set of images (the entrance part of the wooden truss), which would be comparable with all the other systems, were not even oriented; i.e., the process on the server stopped at 18% and showed an error. The second set of images (the back part of the truss) was only partially oriented (Fig. 4). For this reason, the ReCap Photo results were not used in the subsequent comparison with the other systems. This software is obviously suited for more ordinary objects, such as statues or building exteriors. It would be interesting to process the images in the previous version called ReMake, which was also able to process the images locally and with more processing options (higher density, etc.) (3Dscanexpert.com, 2018). However, this functionality is no longer supported.

On the other hand, Agisoft PhotoScan was the only software that could orient all the images automatically. The details from the results of the camera alignment are in Tab. 4. The information about the RMS error on 5 GCPs differs because of the various methods used to align the photogrammetric point clouds to the TLS point cloud. The GCPs were chosen as characteristic points of the timber structure (edges) that were homogenously distributed over the corresponding area of the point clouds.

RealityCapture divided the project after alignment of the cameras into 13 components with partially oriented images. The point clouds from the laser scanning were oriented with 155 images in the main component. There were 6 additional panoramic images created from every laser scan, so there were 60 more images aligned in the main

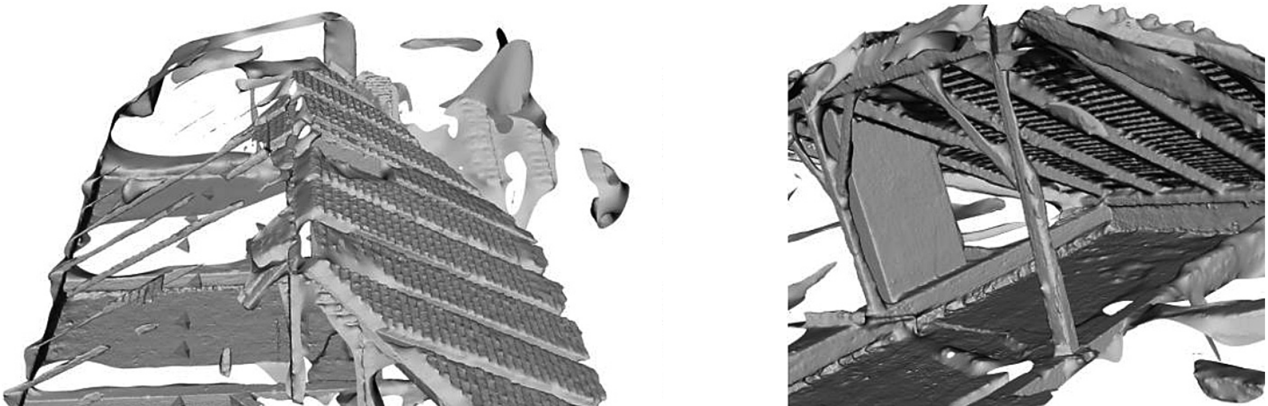

Fig. 4 *Results from Autodesk ReCap Photo (only 20 out of 100 images were oriented).*

Tab. 4 *Results after the alignment of the cameras and georeferencing.*

Software	Oriented photos	Number of tie points	Reprojection error (pixels)	RMS error on 5 GCPs
3DF Zephyr Pro	138	343 362	Mean. 3.20	Aligned with TLS in post-processing
Agisoft PhotoScan Professional	213	414 137	Max. 0.45 RMS 0.15	11 mm
Autodesk ReCap Photo	20	-	-	-
Bentley ContextCapture	173	14 488	RMS 0.72	9 mm
Capturing Reality RealityCapture	155 (215 including TLS images)	1 200 637	Max. 1.99 RMS 0.59	Aligned with TLS during image orientation
Eos Systems Inc. PhotoModeler UAS	130	80 597	Max. 2.83 RMS 0.70	6 mm
VisualSFM (PMVS)	175	60 832	RMS 1.73	-

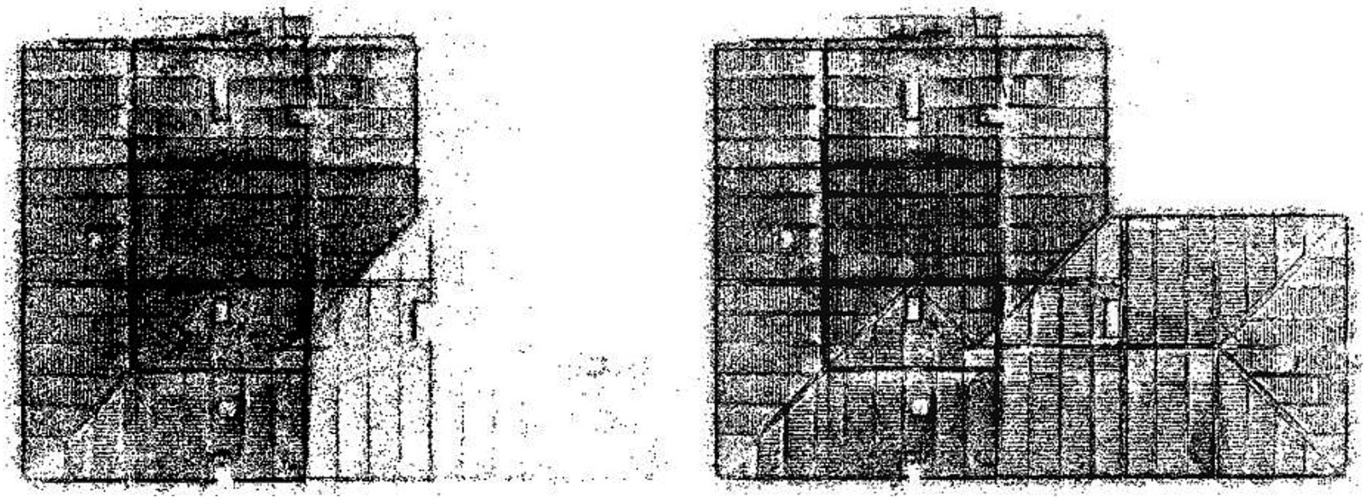

Fig. 5 *Distribution of the tie points from 3DF Zephyr Pro (left) and Agisoft PhotoScan Professional (right) documenting the missing parts of the timber truss structure.*

component (a total of 215). The final dense point cloud that was created only from images consisted of 52.9 million points.

VisualSFM created 5 sets of aligned cameras – 2 of them (with 155 and 20 images) were additionally aligned to each other in the automatic postprocessing. The resulting dense point cloud consisted of 13.8 million points.

All the other systems generated only one basic set of oriented images. 3DF Zephyr produced 22 million, PhotoScan 60 million, ContextCapture 151 million, and PhotoModeler 9 million points in the final dense cloud.

An example of the distribution of the tie points in the 3DF Zephyr and Agisoft PhotoScan solutions is in Fig. 5; all the other systems except Autodesk Recap Photo produced a tie point distribution similar to 3DF Zephyr.

6.2 Amount of detail

An evaluation of the detail and quality of photogrammetric results should never be estimated only through the number of points in a dense point cloud, which can include many outliers. In general, the algorithms used in computer vision meet problems when modelling sharp edges or when the surface texture is of a poor quality. Deformations and misinterpretations of a measured surface can also occur. The selected part of the truss structure is visible in Figs. 6, 7 and 8. The dense point clouds from the various systems were rendered in CloudCompare software (GPL) using the Eye-dome Lighting Open-GL shader.

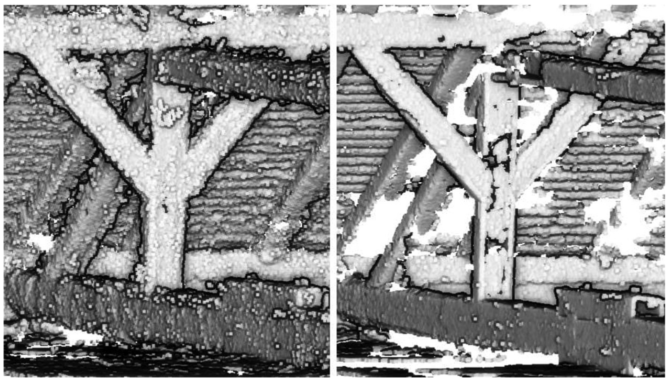

Fig. 6 *Detail of dense point cloud created in PhotoModeler UAS (left) and VisualSFM - PMVS (Right).*

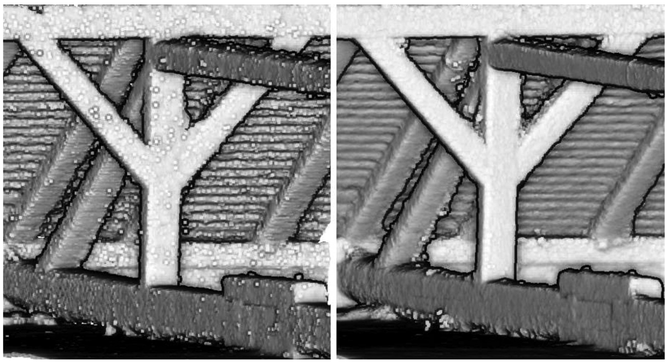

Fig. 7 *Detail of dense point cloud created in 3DF Zephyr (left) and Agisoft PhotoScan (Right).*

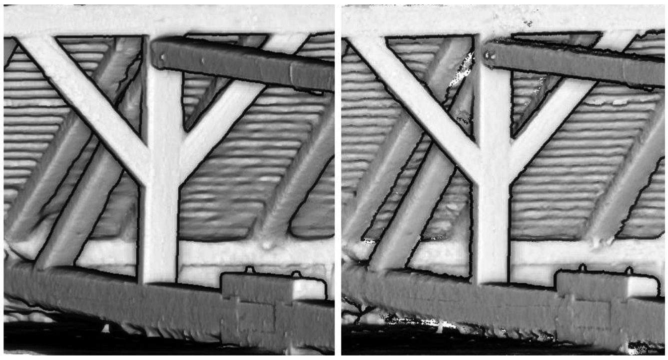

Fig. 8 *Detail of dense point cloud created in ContextCapture (left) and RealityCapture (Right).*

Fig. 6 demostrates that the worst results were obtained using the PhotoModeler and PMVS software. The PhotoModeler results are very noisy. On the other hand, the PMVS results seem to be quite accurate, but very incomplete.

The sharpest and cleanest details were produced using ContextCapture and RealityCapture (Fig. 8). However, the ContextCapture solution is the sharpest only on some parts of the surface; there are areas with blurred purlins and unrealistic components, especially on the edges. PhotoScan is somewhere in between these two systems and the rest, but there is a small amount of noise, and the details are not that sharp (Fig. 7, right). The 3DF Zephyr results look sharper, but are noisier than those of PhotoScan (Fig. 7, left).

6.3 Geometric accuracy

The sharpness of the individual details of the modelled structure is important; however, it is mostly interesting from a visual point of view. If the point cloud should serve as an input for documenting a structure, its overall geometry should be particularly accurate. We can estimate the geometric accuracy of a reconstructed scene by comparing the photogrammetric point cloud to the supposedly more accurate and robust laser scanning point cloud. This was done in the 3DF Zephyr environment, which also enables computing point-to-point distances between imported point clouds (Tab. 5).

Tab. 5 *Statistics from comparison of photogrammetric point clouds relative to the laser scanning point cloud*

Software	Mean diff. (mm)	Stand. deviation (mm)
3DF Zephyr Pro	10.6	8.9
Agisoft PhotoScan Professional	9.6	7.3
Bentley ContextCapture	9.9	8.7
Capturing Reality RealityCapture	7.3	6.7
Eos PhotoModeler UAS	11.0	8.1
VisualSFM - PMVS	8.6	6.4

From Tab. 5 we can see that the PMVS solution has the smallest standard deviation from the TLS point cloud. Similar results were achieved using RealityCapture. However, it is necessary to realize

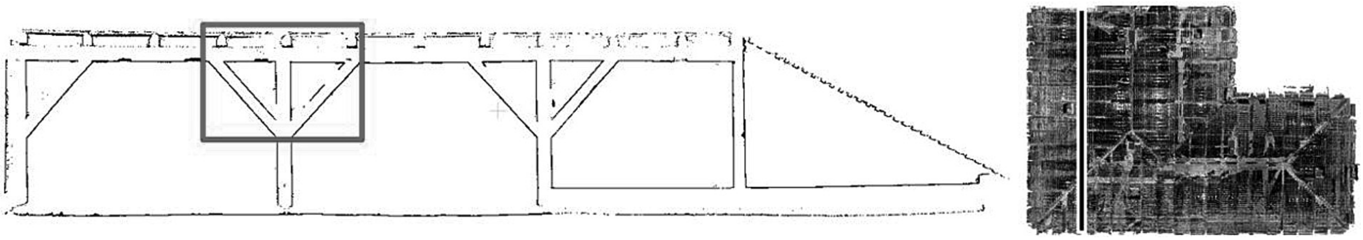

Fig. 9 *Vertical section through a point cloud from laser scanning (left) and its position in the truss structure (right).*

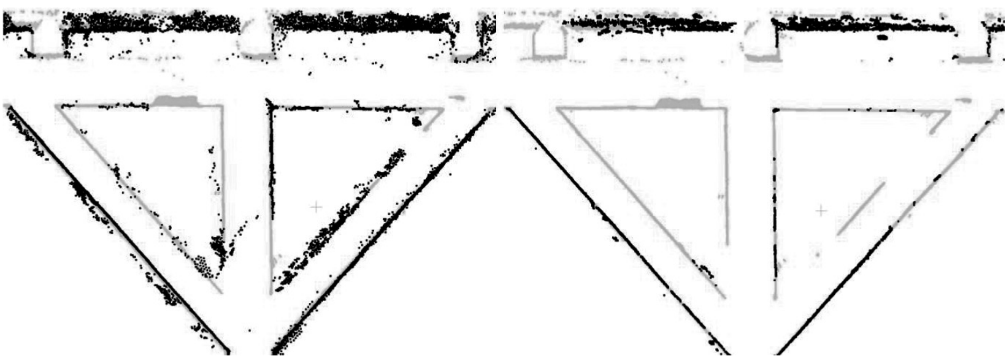

Fig. 10 *Detail of a vertical section through the point clouds from PhotoModeler (left) and VisualSFM-PMVS (right) compared to TLS; the black color represents the photogrammetry.*

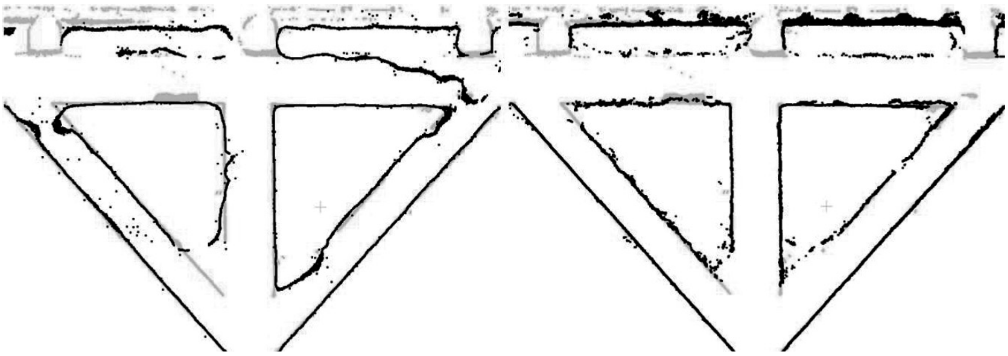

Fig. 11 *Detail of a vertical section through the point clouds from 3DF Zephyr (left) and Agisoft PhotoScan (right) compared to TLS; the black color represents the photogrammetry.*

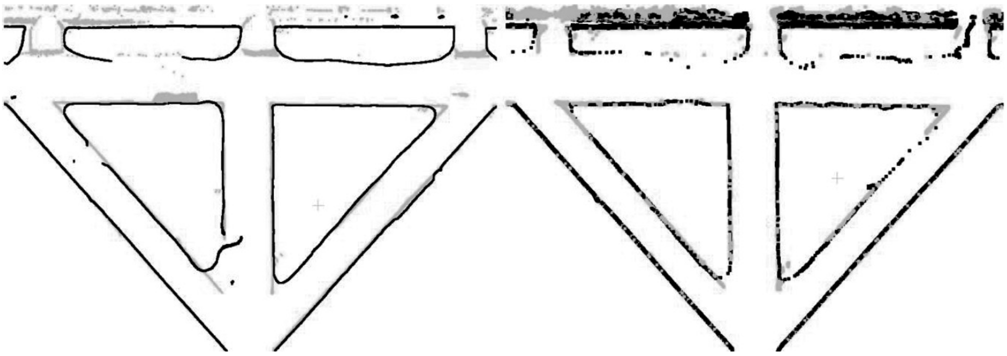

Fig. 12 *Detail of a vertical section through the point clouds from ContextCapture (left) and RealityCapture (right) compared to TLS; the black color represents the photogrammetry.*

that these statistical values are computed from data with various amounts and distributions of outliers and that the existence of these incorrect points may not always be a problem. They can be easily identified and ignored during the vectorization of the significant elements of the structure.

From this point of view, a better way of interpreting the differences between such complicated data would seem to be a visual comparison of the 2D sections. For example, one vertical section was selected (shown in Fig. 9).

The details of this cut (selection of rectangle in Fig. 9) are shown for all the software tested in Figs. 10 – 12.

From Figs. 10 – 12 it is obvious that the distribution of the points describes the actual shape of the structure best with the results obtained with RealityCapture (Fig. 12 on the right). All the other solutions are either noisy, deformed at sharp edges, or incomplete. PhotoScan also achieved very good results. The ContextCapture solution may be very clean and dense, but it generates unrealistic point clusters in various parts of the truss structure, which can lead to unnecessary misinterpretations of the shape of constructions.

From the PMVS results (Fig. 10 on the right), we can see that on one hand, it is partially incomplete, but on the other hand, it is very accurate; better results could be achieved by adjusting its computational parameters in the settings file, but that is not very user friendly and leads to the "trial and error" method.

If we ignore the significant deformations at the sharp edges and create 2D-layout shapes of the individual structural components based on the main section lines, it is crucial how accurate the position and direction of these lines are. When we measured the shortest distance between the lines extracted from the sections through the photogrammetric and laser scanning point clouds (the perpendicular distance between the subject lines), there were the biggest differences of 10 mm, specifically in the PhotoScan results. RealityCapture produced results with negligibly small differences to the TLS, which is logical if we realize that the relative orientation of the cameras was automatically adjusted to fit the laser scans. Anyway, the main source of the maximum 10 mm differences could be found in the manual georeferencing with naturally signalized GCPs. More accurate results could be achieved when using artificial contrast targets.

7 DISCUSSION

An accuracy of 10 mm is sufficient for most architectural applications such as the surveying of the actual state of a building's structure. The fact that all the systems tested achieved this degree of accuracy in the main parts of the timber structure demonstrates a strong camera network configuration and minimum geometric deformations of the reconstructed scene. However, each software produced different results, especially at the sharp edges and in the small details. An interesting insight is also the fact that this degree of accuracy was achieved without the use of artificial GCPs surveyed with a total station. Identical (GCP) points between the point cloud from TLS and photogrammetry were measured manually with respect to the characteristic elements of the timber structure (sharp edges). Nevertheless, this was possible only thanks to a sufficiently dense point cloud from the laser scanning (a density of 3 mm).

We do not want to judge which software is better, and it is possible that after more testing of various settings, better results could be achieved with every one of the mentioned systems. But the results presented sufficiently document the strengths and weaknesses of the individual software solutions. Lastly, these tests were performed on a specific object, and it is possible that the individual software will behave differently on objects with other structures and textures.

Significant problems were met during the automatic alignment of the images; only the Agisoft PhotoScan was able to align all the photos, which confirms its universality and robustness for special field situations. But this problem could be solved by taking more images in the field and with greater overlaps, if possible. More images can lead to more time-consuming processing; however, the individual systems are also different in computing power, and some are significantly faster than others. Various comparisons were done and presented online that show the interesting results achieved, especially with RealityCapture, concerning computational time (www.pi3dscan.com, 2015).

Another great advantage of the software solutions selected is the option of importing point clouds from various sources, e.g., TLS. From this point of view, the best results are achievable using RealityCapture, because it can adjust camera positions relative to the laser scans and also make the camera network more accurate in very complex environments. Semiautomatic alignment of a dense photogrammetric point cloud with a TLS point cloud is also available in 3DF Zephyr; however, there is no possibility of adjusting the relative camera orientation, and the software only uses the basic spatial conformal transformation (3 translations, 3 rotations, 1 scale factor) to transform the final dense point cloud.

From the vertical section through the laser scans (Fig. 9), we can see missing parts of the structure that were caused by occluded areas during the scanning. This is a very common problem caused by the sometimes limited options for TLS placement in complicated structures. The adding of photogrammetric point clouds to laser scans seems to be an ideal solution if we need to achieve data sets describing the complete surface of the structure measured.

8 CONCLUSION

Seven different photogrammetric systems based on SFM technology were tested in this contribution. Identical sets of images of a wooden truss were processed in 3DF Zephyr Pro, Agisoft PhotoScan Professional, Autodesk Recap Photo, Bentley ContextCapture, Capturing Reality RealityCapture, Eos Systems Inc. PhotoModeler UAS, and VisualSFM with the support of PMVS software. All the software mentioned produced different results at various steps of the 3D scene reconstruction process.

All the images were only aligned by Agisoft PhotoScan; the remaining software were able to align only three quarters of the set data. In the corresponding parts of the timber truss structure, a dense point cloud was computed, and a comparison was done from various points of view. This mainly included the amount of detail reconstructed and the accuracy of the geometric representation of the individual components of the truss structure. The photogrammetric point clouds were compared to the laser scanning point cloud; point-to-point distances were computed; and vertical sections through selected parts of the structure were analyzed.

In recent years, the measurement of wooden trusses has mostly been a domain of laser scanning; however, the results obtained show the great potential of photogrammetric systems based on SFM technology in the sector of civil engineering and complex structures. A combination of both technologies seems to be very effective, especially in hard-to-reach and narrow spaces and can help produce more complex results by taking advantage of different data acquisition principles.

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