A trustable 3D photogrammetry approach for cultural heritage

(Article begins on next page)

A trustable 3D photogrammetry approach for cultural heritage

Leila Es Sebar
Emma Angelini
Sabrina Grassini
Dipartimento di Scienza Applicata e Tecnologia
Politecnico di Torino
Email: leila.essebar@polito.it

Marco Parvis
Luca Lombardo
Dipartimento di Elettronica e Telecomunicazioni
Politecnico di Torino
Torino, ITALY
Email: luca.lombardo@polito.it

***Abstract*—Photogrammetry is a non-invasive technique that is acquiring major importance for documentation and construction of 3D models. Nowadays, many 3D models are created and shared, with only few information about the trustworthiness of the final model. In general, it is possible to have only basic statistical information and quality descriptors related to the software processes. Therefore, the authors propose a novel approach that trough the use of a standard object within the acquisition scene allows one to check to overall quality of a model with trustworthy metric information. Archiving and sharing 3D models, even if nowadays thanks to many commercial and open source software is an easy task, could be a tricky procedure. Indeed, a model could be a photorealistic reproduction and at the same time it could carry wrong metric information. In the field of cultural heritage, in which photogrammetry is a technique applied for documentation, monitoring, dissertation and archiving, sharing incorrect data should be an avoided practice. This paper presents the developing of a specific 3D standard for the photogrammetry process characterization and discusses the new experimental approach proposed.**

***Index Terms*—photogrammetry, 3D model, cultural heritage, non-destructive**

I. INTRODUCTION

Photogrammetry is the science of collecting three-dimensional information about geometry, color and texture of an object. This is a process that, starting from the acquisition of digital images, leads to the construction of a 3D model. Nowadays, photogrammetry is increasingly diffused in several fields and in particular in the cultural heritage area. Indeed, with a 3D survey of an object it is possible to perform a complete documentation and therefore a digital archiving of any artefact.

Furthermore, the 3D model can be useful in case of damage or loss of an artefact, in virtual museums, for education purposes [1] and for innovative presentation for disadvantaged users in museums with tactile exhibitions [2].

With the diffusion of easy-to-use software, available both for computers and smartphones, creation and display of a 3D model is a procedure that almost everyone can succeed in. Unfortunately, learning how to use such user-friendly and automatic software, do not always lead to models with a metric reliable result, i.e. with a model where it is possible to obtain dimensions with a specified uncertainty. Indeed, even though the process of automatic photogrammetry in many cases seems an easy task, the quality of the final model is an aspect that is often underestimated, mostly if the final purpose is monitoring and archiving.

Accuracy and reliability of the final results depends on two main aspects: the acquired data quality and the experimental procedure employed for the reconstruction process.

The acquired image quality is an essential element of the reconstruction workflow on which the entire work rely upon. The image acquisition must be performed in order to have clean and sharp images (good resolution, contrast, exposure, etc). Therefore, the methodology known as the “3x3 CPA rules” is usually employed. These simple rules, regarding geometry, camera and procedure, were presented in [3] and updated in [4] to make them suitable to the recent developments in photogrammetry. In this procedure, the camera is not required to be precisely positioned and this greatly helps acquiring the images without specific problems; however, not satisfying this basic requirements usually leads to a failure of their manipulation with the software and therefore to a failure of the final aim of a metric trustworthy 3D relief.

Once the images have been acquired an algorithm is used to extract geometrical information about the object under study.

Nowadays, many commercial software, such as Metashape, 3DF Zephyr, RealityCapture etc. and open source solutions such as `COLMAP`, `MicMac`, `Regard3D`, `VisualSfM`, `openMVG`, `PMVS` are available. Some of the software are easier to use and work as an user-friendly black box solution even thought with no control on the process, other require tuning and used intervention [5], [6].

In all cases, as deeply discussed in [7], the 3D photogrammetry process for obtaining a model of an object, requires at least five successive steps:

1) The interior orientation and camera calibration procedures
2) The exterior orientation: from stereoscopic models to SfM
3) Structure from motion
4) The geometry reconstruction
5) Mesh and texture generation.

At the end of the whole process, the output is a 3D model with information regarding the artifact geometrical features and colors, but without a predefined scale as the software is usually not capable on doing it.

In order to obtain a metric trustworthy model of the object it is therefore necessary to scale it. To this aim, specific elements are added to the acquisition scene. One example is the addition of coded-targets that specific software are able to automatically detect (e.g. Metashape). Metric scale are sometime added as well. Therefore, the absolute distance data related to the 3D model quality cannot be better than the target dimension accuracy however the correlation of the point to point distance is not affect by this element and depends of process statistic evaluation, through the investigation of quality descriptors obtained with statistical methods reported in [8].

In the field of Cultural Heritage there is a considerable interest in the use of photogrammetry as a tool for recording and archiving data on artefacts and structures in order to develop tailored methodologies for ensuring their long-lasting preservation and fruition and to have the possibility of making widely available models of objects which cannot be made available to the public and need to be preserved for the future generations [9]. Therefore, there is a growing concern about the reliability of collected data.

Final aim of this paper is therefore to present an alternative approach respect to the statistic evaluation [8], in order to determine the final model accuracy, which can be eventually implemented by adding information on the materials, on the degradation mechanisms, on the conservation state and so on.

II. The proposed solution

A. Foreword

The proposed solution employs a simple standard object whose dimensions are known and which is used both for calibrating the model and to verify the accuracy of the reconstructed data. The proposed approach can be used with several different types of photographic camera, lens and software, however in the following all the results have been obtained by employing a simple commercial Nikon camera and an open-source software (`MicMac`) commonly used in photogrammetry.

B. 3D-STD: a 3D printed standard

The first step of the proposed process is the design of a new object standard. Such a standard, referred to in the following as 3D-STD, has to fulfill some requirements to be suitable for the photogrammetry reconstruction process and to allow the 3D software to work.

- The 3D-STD has to be designed in order to have amorphous geometries with several different faces 'randomly' oriented to resemble a real object. This is extremely important since arranging a simple geometrical standard might not only fool the reconstruction software, but also give underestimated uncertainty results.
- The 3D-STD has to contain elements with different sizes, positioned in different parts and not visible from all points of view so that it is possible to test the model for different dimensions and after having rotated it according to different views.
- Since in most cases the software rely on black-and-white images, the color cannot be used as a distinctive element of the different part for the 3D-STD. From one point of view this make easier to create the standard, but also limits the freedom of the standard designer.
- The different faces, must contain many corresponding image points [10] whose position can be easily determined in the space.

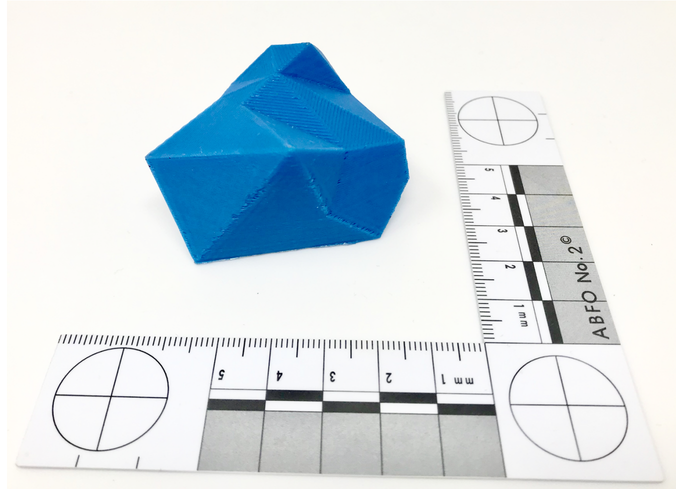

Fig. 1. Example of the object realized by the WASP 3D printer in PLA, along with a commercial angular scale.

To quickly reach this aim and produce a low-cost and simple 3D-STD suitable for testing the proposed approach a simple 3D printer has been used. This is not of course the best way of arranging the 3D-STD as a more expensive metal standard would provide a lower uncertainty, however the approach let users to obtain the 3D-STD through an easier and faster process.

A 3D multi face model was developed with Wings3D and eventually the standard was realized in polylactic acid (PLA) by the 3D printer. Fig. 1 shows an example of the 3D-STD. This way, the print process can be easily carried out by means of the low-cost single-extruder 3D printer manufactured by WASP (WASP2040). The printer has been used with an extruding speed of $150\ \mathrm{mm/sec}$ and with a layer thickness of $50\ \mu\mathrm{m}$ to reduce the uncertainty of the standard realization. The entire printing process lasts less than $100\ \mathrm{min}$.

The 3D-STD prototype has a dimension of $55\ \mathrm{mm} \times 40\ \mathrm{mm} \times 30\ \mathrm{mm}$ and an external surface composed of 28 faces. The intersection between the different faces (22) have a position in the space which is known within $50\ \mu\mathrm{m}$ and which depends on accuracy the printer is capable of producing and on the stability of the plastic final standard.

The 3D-STD edges were eventually measured by means of a caliper with sensitivity $50\ \mu\mathrm{m}$.

TABLE I
NIKON D3100 CAMERA SPECIFICATIONS

Image size (pixels)	4608 × 3072
Effective megapixels	14.2
Sensor size, type	23.1 x 15.4 mm CMOS sensor
Pixel size (μm)	4.94
ASA/ISO range	100–3200 in 1/3 EV steps, up to 12800 as boost

TABLE II
AF-S DX ZOOM-NIKKOR 18-55MM F/3.5-5.6G ED SPECIFICATIONS

Focal length range	18-55mm (35mm equivalent 27-82.5mm)
Maximum aperture	f/3.5-5.6
Minimum aperture	f/22-38
Zoom ratio	3.1x

C. Image acquisition

All images were acquired by using a NIKON D3100 camera equipped with an AF-S DX ZOOM-NIKKOR 18-55mm f/3.5-5.6G ED lens. Technical specifications of camera and lens are listed in Table I and Table II.

The camera had a fixed position at a distance of about 60 cm from the object, it was tripod mounted and the remote trigger function was used in order to avoid touching the camera during acquisition. The 3D-STD was placed on a turntable put inside a photographic tent. The tent is equipped with a set of LED lights with a color temperature of 4000 K, which are diffused from the white inner tent coat, in order to avoid any shadows during the shooting. Fig. 2 shows the experimental setup where the tent has been opened for clarity.

Images have been acquired insuring an overlap of more than 60% between images. After some preliminary tests, the lens focal length was set to 18 mm with a fixed aperture of $f/6.3$, the exposure time to was set to $1/125$ s and the camera sensitivity was set to $ISO400$. All images were acquired in RAW format. The images acquisition procedure required less than one hour.

A calibrated printed sheet (fig. 3) was put under the 3D-STD to check for the final accuracy and help scaling the final model.

D. 3D reconstruction via MicMac software

As told before, all tests have been performed by using the `MicMac` software. `MicMac` is an acronym for `Multi-Images Correspondances, Méthodes Automatiques de Corrélation`, and is an open source program developed by the French National Geographic Institute (IGN). It allows one to complete each phase of the photogrammetry workflow, from tie points search to the texture generation and eventually the model scaling, by operating on different software programs. Indeed it is possible for the user to process the data by means of simple line commands, with no need of setting advanced parameters. Otherwise, a more expert user can change the

Fig. 2. Example of the setup used to acquire the images by using a photographic tent and a Nikon D3100. The image shows the camera, the turntable, the 3D-STD placed on a rectangular scale and the remote camera control which is used to avoid any image movement.

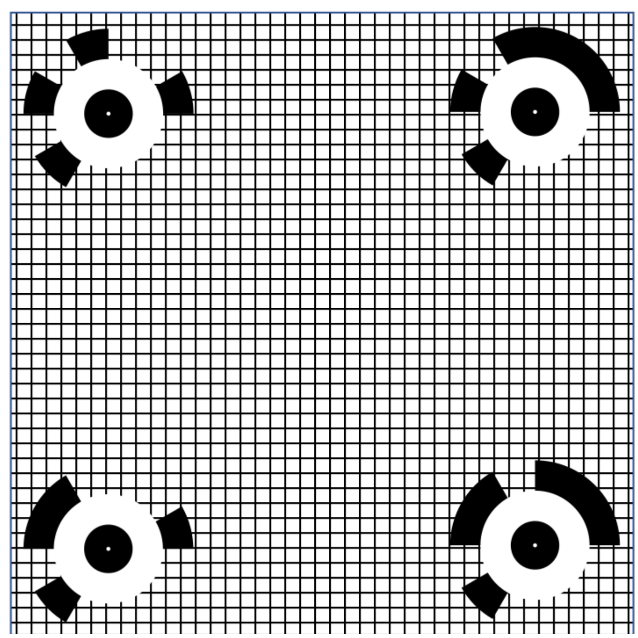

Fig. 3. The calibrated sheet put under the artifact.

parameters default values in order to achieve the desired result. According to the programmers, the software “stresses the aspects of accuracy, reliability, and makes available tools typically unavailable in existing software alternatives” [16], [17].

Data processing was performed following the pipeline proposed by the `MicMac` software.

- The initial step regards the identification of homologous points on picture pairs. This is done with the $Tapioca$ tool, based on the SIFT++ algorithm [18], [19].
- The the optical properties of lens and sensor were computed thanks to $Tapas$.
- The cloud point with camera positions were produced thanks to the $AperiCloud$ tool and are saved in a .ply file (Fig.4a).
- $Metashape$ and $CloudCompare$ were used to check for the cloud point correctness
- The $C3DC$ tool was used to compute a dense cloud point from the already oriented images (Fig.4b).
- $SaisieBascQt$ was used to scale the 3D image based on the distance between points on the artifact.
- $SBGlobBascule$ was used to create a new orientation folder, with the desired scale factor applied.
- The Poisson algorithm [20], [21] was used for the mesh generation, by using $TiPunch$ (Fig.4c).
- $Tequila$ was used to add a texture to the final results (Fig.4d).

The `MicMac` software determines more than 65000 points which are used by the $C3DC$ to created a dense cloud of about half million points. The mesh generated by $Tequila$ contains about hundred thousand faces.

Fig. 4 shows some of the outputs from the previous steps till the final result, which is shown at figure bottom.

E. Model performance

Assessing the mode uncertainty is a complex task, since it involves measuring points in the space on the 3D-STD and calibrate the model itself.

Several parameters can be used and, taking into account that the model can be used to rotate the object so that no predefined orientation can be assumed, the authors decided to compute the distance between homologous points on model and standard.

Of course such a difference depends on the model orientation and can become quite high [22], due to the amplification related to the actual orientation especially if the points on the model become at the end of their point of view. To minimize this problem all model measurements were performed having both points well inside the visual area. Fig. 5 shows some of the selected distances, which are on different parts of the standard and cover sizes in the range of about 9 mm to 40 mm

The model uncertainty can be defined either according to the difference δ as :

$$\delta = |\mathbf{M_{object}} - \mathbf{M_{model}}| \tag{1}$$

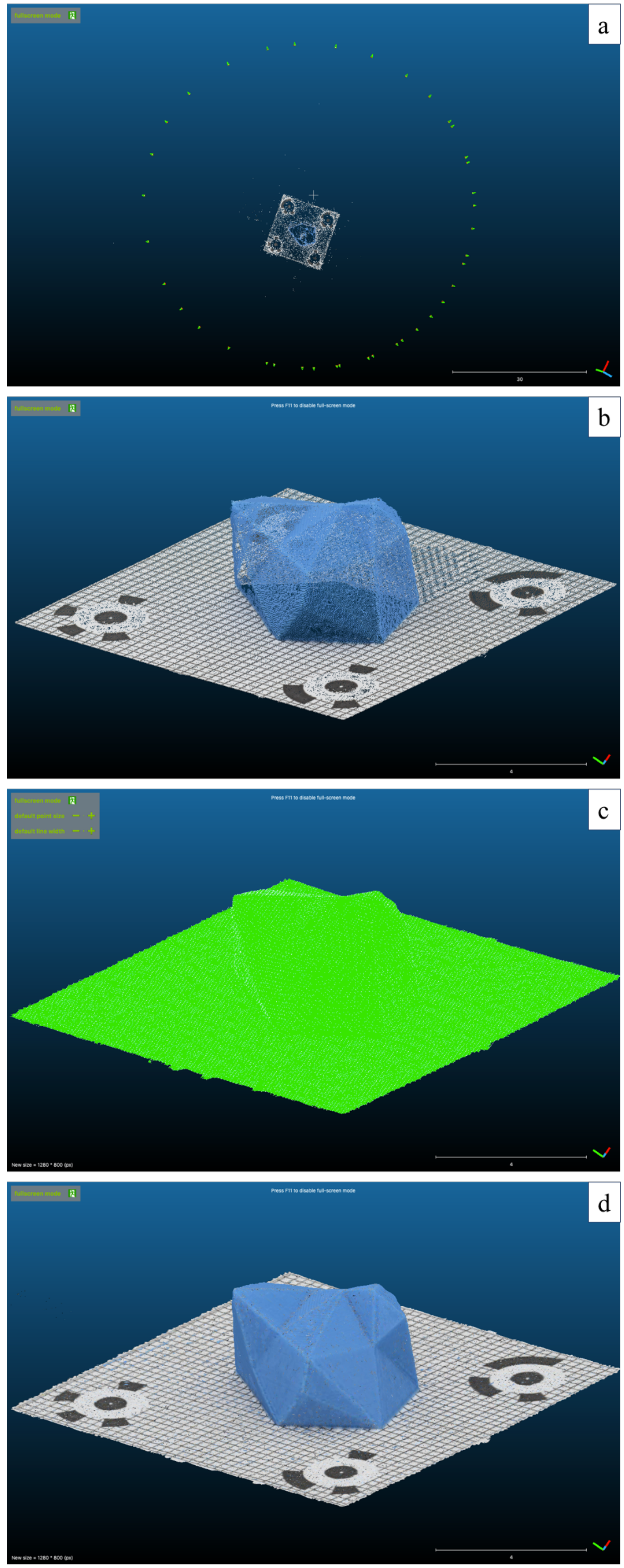

Fig. 4. Outputs from the different steps of the MicMac process: a) sparse point cloud and camera positions; b) dense point cloud; c) 3D mesh; d) textured 3D final model.

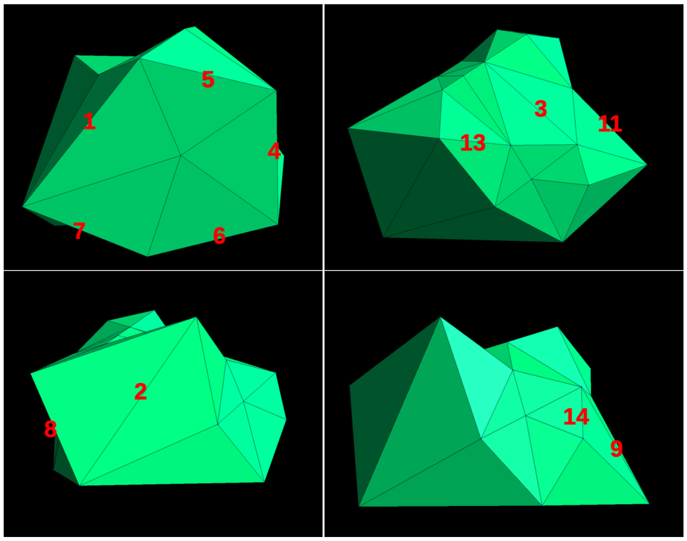

Fig. 5. Distances on the standard used for the model assessment. Since the model can be rotated, the distances have been selected on different views. Not all the points shown for avoiding a too large image. The results obtained on the model and their uncertainty are reported in Table III .

where $\mathbf{M_{object}}$ and $\mathbf{M_{model}}$ are the 3D distances between the same points of model and 3D-STD, or according to the relative uncertainty (2).

$$\epsilon = \frac{|M_{object} - M_{model}|}{M_{object}} \tag{2}$$

A single synthetic value, suitable to characterize all the software, can be obtained by computing the overall standard deviation (3):

$$std = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\delta_i)^2} \tag{3}$$

Table III shows the obtained results on the distances shown in fig. 5. The table shows distances on the 3D-STD and the corresponding distances on the model. The model has preliminary scaled as discussed in the text and the scaling has been later adjusted so that the mean difference between standard and model is zero. The required scaling change was of about 0.3% confirming the initial model scaling correctness. Distances on the 3D-STD have been measured with the caliper and the estimated uncertainty of each distance is shown, distances on the model do not have any associated uncertainty as the software does not provide it. Table rows are shown in descending order of size.

Table III also reports the distance difference δ in $\,\mathrm{mm}$ and the corresponding relative error ϵ. At table end also the standard deviation std is shown along with the standard deviation of ϵ.

By considering the data reported in Table III it is possible to conclude that the maximum difference in estimating the distance between two points does not usually exceed $1\,\mathrm{mm}$ with a standard deviation of about $0.6\,\mathrm{mm}$. Most of the differences are related to the difficulty of identifying on the model the points already measured on the 3D-STD due to the difficulty the software has in modeling sharp cuspid points.

TABLE III

3D-STD-MODEL COMPARISON FOR DIFFERENT DISTANCES. THE MODEL SCALING HAS BEEN PERFORMED AS DESCRIBED IN THE TEXT AND ADJUSTED BY 0.3% TO MINIMIZE THE OVERALL DIFFERENCE.

Distances	**Standard [mm]**	**Model [mm]**	**δ [mm]**	**ϵ [%]**
1	39.50 ± 0.1	39.12	-0.38	-0.96
2	39.50 ± 0.1	38.93	-0.57	-1.44
3	34.00 ± 0.1	33.00	-1.00	-2.94
4	28.00 ± 0.1	27.26	-0.94	-3.34
5	27.50 ± 0.1	27.85	0.35	1.28
6	27.20 ± 0.1	27.61	0.41	1.51
7	26.80 ± 0.1	27.10	0.30	1.11
8	24.40 ± 0.1	24.06	-0.34	-1.40
9	23.65 ± 0.1	23.83	0.17	0.75
10	21.60 ± 0.1	22.79	1.19	5.52
11	21.30 ± 0.1	21.80	0.50	2.34
12	12.20 ± 0.1	12.69	0.49	4.02
13	10.00 ± 0.1	10.25	0.24	2.46
14	9.40 ± 0.1	0.96	-0.44	-4.66
	Standard Deviation		0.62	2.9

The uncertainties are not negligible so that the open-source software need probably to be tuned to decrease these values. Also no clear correlation in the distances appears as the distance values changes confirming the proposed solution is suitable for the calibration. One should also note that the 3D-STD uncertainty ($100\ \mu$m) in this case can be considered negligible with respect to the final difference so that there is no need to arrange a better 3D-STD prototype, at least until the `MicMac` software has been updated.

III. CONCLUSIONS AND FUTURE WORK

This paper presented development and realization of an innovative standard, referred to as 3D-STD, that can be used during the creation of 3D models of different objects. The 3D-STD can be placed within the acquisition scene and provide a 3-dimensional reference, that allows one to scale the desired final model and to estimate its metric trustworthiness.

By simply using an open-source software out of the shelf, a standard deviation uncertainty of about $0.6\,\mathrm{mm}$ on size of the order of $40\,\mathrm{mm}$ has been obtained. While this value is in-line with was expected, there is room for improvements which can be easily obtained since the software is open source.

Future work also include the improvement of the proposed 3D-STD to arrange a device suitable for creating hyper-spectral photogrammetry standards and to embed into the 3D-STD also the capability of calibrating models working outside the visible wavelength (UV, IR, X-Rays, etc.).

REFERENCES

[1] F. Remondino and S. El-Hakim, Image-based 3D Modelling: A Review: Image-based 3D modelling: a review, The Photogrammetric Record, vol. 21, no. 115, Aug. 2006, pp. 269–291

[2] D. Karastoyanov, N. Stoimenov, and S. Gyoshev, Innovative Approach for 3D Presentation of Plane Culturally-Historical Objects by Tactile Plates for Disadvantaged Users (low- sighted or visually impaired), MATEC Web of Conferences, vol. 292, 2019, p. 03004.

[3] P. Waldhäusl, C. L. Ogleby, 3 x 3 rules for simple photogrammetric documentation of architecture, International Archives of Photogrammetry and Remote Sensing, 30, 1994, pp. 426–429.

[4] TheoLt 2010 Photography For Photoplan3d: The 3×3 Rules. Available at: http://www.theolt.com/web/ photography-for-photoplan3d-the-3x3-rules/

[5] S. Altman, W. Xiao, and B. Grayson, "Evaluation of low-cost terrestrial photogrammetry for 3D reconstruction of complex buildings", ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. IV-2/W4, Sep. 2017, pp. 199–206.

[6] M. Daneshmand et al., "3D Scanning: A Comprehensive Survey", arXiv:1801.08863 [cs], Jan. 2018.

[7] I. Aicardi, F. Chiabrando, A. Maria Lingua, and F. Noardo, "Recent trends in cultural heritage 3D survey: The photogrammetric computer vision approach", Journal of Cultural Heritage, vol. 32, Jul. 2018, pp. 257–266.

[8] A. Calantropio, M. P. Deseilligny, F. Rinaudo, and E. Rupnik, "Evaluation of photogrammetric block orientation using quality descriptors from statistically filtered tie points", ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLII–2, May 2018, pp. 185–191.

[9] H. M. Yilmaz, M. Yakar, S. A. Gulec, and O. N. Dulgerler, "Importance of digital close-range photogrammetry in documentation of cultural heritage", Journal of Cultural Heritage, vol. 8, no. 4, Sep. 2007, pp. 428–433.

[10] M. Schaich, "Combined 3D scanning and photogrammetry surveys with 3D database support for archaeology and cultural heritage". A practice report on ArcTron's information system aSPECT3D. Photogrammetric Week'13, 2013, pp. 233–246.

[11] I. Nikolov and C. Madsen, "Benchmarking Close-range Structure from Motion 3D Reconstruction Software Under Varying Capturing Conditions", in Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection, Cham, 2016, pp. 15–26.

[12] J. Schöning and G. Heidemann, "Evaluation of Multi-view 3D Reconstruction Software", in Computer Analysis of Images and Patterns, Cham, 2015, pp. 450–461.

[13] Z. Champion, F. Chiabrando, and J. Harrington, "3D modeling of the Michigan Tech Husky statue using a close-range photogrammetric approach", Imaging and Geospatial Technology Forum, IGTF 2015 - ASPRS Annual Conference and co-located JACIE Workshop, Jan. 2015, pp. 243–254.

[14] P. Grussenmeyer and O. Khalil, "A comparison of photogrammetry software packages for the documentation of buildings", May 2008, halshs-00281254.

[15] F. Alidoost and H. Arefi, "Comparison of UAS-based photogrammetry software for 3d point cloud generation: a survey over a historical site", ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. IV-4/W4, Nov. 2017, pp. 55–61.

[16] E. Rupnik, M. Daakir, and M. Pierrot Deseilligny, "MicMac – a free, open-source solution for photogrammetry", Open Geospatial Data, Software and Standards, vol. 2, no. 1, Dec. 2017.

[17] J. Friedt, Photogrammetric 3D structure reconstruction using Micmac, 2014.

[18] M, Pierrot-Deseilligny, I. Cléry, "APERO, an Open Source Bundle Adjusment Software for Automatic Calibration and Orientation of a Set of Images", Proceedings of the ISPRS Commission V Symposium, Image Engineering and Vision Metrology, Trento, Italy, 2011.

[19] A. Vedaldi, "An open implementation of the SIFT detector and descriptor", Technical Report 070012, Computer Science Dept., Univ. of California, Los Angeles, USA, 2007.

[20] M. Bolitho, M. Kazhdan, R. Burns, H. Hoppe, "Parallel on Surface Reconstruction", In Advances in Visual Computing, Springer Berlin Heidelberg, 2009, pp. 678–689.

[21] M. Kazhdan, M. Bolitho, H. Hoppe, "Poisson surface reconstruction", In Proceedings of the fourth Eurographics symposium on Geometry processing, Vol. 7, June 2006.

[22] RFC7459 Representation of Uncertainty and... freely available at `https://www.rfc-editor.org/rfc/pdfrfc/rfc7459.txt.pdf`, last checked on November 25, 2019