An updated comparison on contemporary approaches for digitization of heritage objects

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An Updated Comparison on Contemporary Approaches for Digitization of Heritage Objects

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***Abstract* – Continuous developments on sensors, data acquisition techniques, algorithms and computational systems have enabled automation, higher processing velocities and increased metric accuracy regarding the modeling of tangible heritage. For applications on heritage artefacts or architectural details, scanning and photogrammetric systems based on structure-from-motion (SfM) approach have prevailed, due to lower costs, fast acquisition and processing, re-producibility of workflows and ability to capture high-resolution texture. This study presents an updated comparison of contemporary digitization approaches to examine in extent required processing stages, compare costs and evaluate produced 3D results according to their metric properties, quality of texture and visual fidelity.**

I. INTRODUCTION

The crucial importance attributed to three-dimensional documentation of cultural heritage by the international scientific community, is directly related to the needs of protection, preservation and valorization. Some of the application fields include digital repositories, VR/AR, high-resolution physical copies, digital reconstructions, diagnostics, conservation and monitoring [1].

The continuous development of numerous new sensors, data acquisition techniques, algorithms and computational systems, used to recover three-dimensional characteristics of tangible heritage, but also the improvement of existing ones, constitute a significant contribution to the recording, processing and visualization of data about heritage objects. These developments have enabled automation, higher velocities and, sometimes, increased accuracy. The advancements on digital technologies, such as handheld scanners and image-based automated or semi-automated software, provide powerful digitization tools to experts and end-users both [2]. For the cases of very-large-scale digitizing (artefacts, archeological excavation in-situ documentation, historical architecture details, historical materials) products of milli-metric or sub-milli-metric resolution may be required. Thus, providers of the heritage 3D models should not only be aware of the state-of-the art on the field, to try and minimize cost and time, but also to effectively communicate with heritage. Meaning, that metric needs should be well defined before the digitization process, as they have a great impact on acquisition and processing equipment and workflows [3].

Accurate and high-texture-fidelity heritage modeling has been investigated with a variety of active and passive sensors to reconstruct both geometry and texture. Laser scanning [4], structured light scanning [5], range camera sensing [6], image-based photogrammetric modeling [7], [8], [9] are techniques explored for the digitization of heritage. Although, triangulation laser scanning, structured light scanning and photogrammetric systems based on SfM approach [10] have prevailed for large-scale heritage applications, mainly due to combined: lower costs, fast data acquisition/processing, reproducibility of workflows and ability to capture high-resolution texture details. Many contemporary workflows combine more than one technique to optimize the resulting digital models [11].

Comparisons regarding abovementioned techniques can often be found in bibliography, even though they easily become outdated, due to fast updates of SfM software and scanning instruments. Extensive comparisons have been carried out on heritage objects, by Remondino et al. [12] Galizia et al. [13], Bianconi et al. [14] for SfM software, by Evgenikou and Georgopoulos [15] and Menna et al. [16] on scanning versus SfM photogrammetric software approaches and by Kersten et al. [17] for the accuracy of handheld scanners.

Metric modelling of heritage is comprised of three parameters: the object (size, geometry, texture, materials), the acquisition (sensor, conditions, planning of referencing or scaling, survey) and the processing (software, algorithms, workflows, final products). If at least one of the abovementioned parameters is stable, then some comparison can be made between the results.

In the first part of the presented research, a thorough comparison between SfM photogrammetric workflows is performed by maintaining stable objects and acquisition step. Secondly, a comparison between handheld scanners, and lastly by keeping as a constant only the objects a comparison between photogrammetric and scanning models. Specific importance is also given in this paper, not only to compare metric and visual results but also prices and duration of the processing workflows as they are crucial factors for choosing instrumentation and software for heritage modeling, especially in cases of in-situ, mass or rapid digitization. The test objects for this study were a copy of Early Cycladic II Spedos-variety marble figurine, dimensions: 4cm x 4cm x 16cm (herein referred to as OBJ1) and a copy of Roman column capital, dimensions: 45cm x 45cm x 45cm (herein referred to as OBJ2).

II. PHOTOGRAMMETRIC TESTS

A. Data Acquisition

For the photo shooting session a full-frame DSLR Canon EOS 5DS R at 52 MP (3,500€) with a Canon EF 24-105 mm lens (750€) along with a tripod have been used. For OBJ1, 50 images were acquired sequentially in a circular pattern and employed with a large overlapping over the object area (90%), using a turntable and a step of approx. 8 grads. They were acquired with a focal length of 24 mm, with exposure set to 1/20 sec at f/7.1 ISO 400 at an average distance of 26 cm, resulting in a DoF of 5 cm and an object resolution of 0.05 mm /pixel. For OBJ2, 100 oblique images were acquired unordered to completely cover its geometry. It was acquired with a focal length of 35 mm, with exposure set to 1/40 sec at f/7.1 ISO 800 at an average distance of 91 cm, resulting in a DoF of 28.5 cm and an object resolution of 0.10 mm /pixel.

B. Processing

The photogrammetric solutions employed included one workflow combining open and free software for different processing steps and four commercial software -one of which was web based- as follows:

i. combined free solution with VisualSFM [18], [19], [20], [21], and Meshlab [22], [23]
ii. Agisoft Metashape Pro (3,077€)
iii. Pix4Dmapper (3,990€/ Pix4Dmodel 49€ /month)
iv. 3DFlow Zephyr Aerial (3,900€)
v. ReCap Photo (1,104.10 € for three years or 48.80€ /month -with ReCap Pro) (web-based)

Processing solutions are herein referred to respectively with the abbreviations VSfM, AMP, P4D, FZA and RCP.

For the processing of OBJ1 dataset an ASUS portable laptop was used, with a quad-core Intel i7-4710 CPU at 2.5 GHz (Max 3.5 GHz) with 16 GB RAM. For the processing of OBJ2 dataset a SANTECH portable laptop was used, with a hexa-core Intel i7-8750H CPU at 2.2 GHz (Max 4.1 GHz) with 32 GB RAM.

For the image dataset of OBJ2 it was decided to use similar parameters (when applicable) for all image-based modeling workflows to compare the times for production of similar volumes of results. For the dataset of OBJ1 it was decided to use mostly the default parameters of the software to also compare produced volumes of results.

Table 1: Parameters for photogrammetric processing.

	OBJ1	OBJ2
Matching + Alignment		
Accuracy/Matching type	high	high
Pair preselection	circular	unordered
Key point limit	default	50,000
Tie point density	high	5,000
Camera model fitting	default	adaptive
Dense Matching		
Masks/Annotations	yes	no
Point density	default	high
Depth filtering	default	low
Mesh Generation		
Max number of faces	default	1,500,000
Interpolation	default	enabled
Texture Generation		
Max octree depth	9	14
Texture size	8,192	8,192
Color balancing	disabled	disabled

C. Results

Assessment of quality of produced 3D meshes and textures considered: completeness, preservation of surface detail, levels of noise, roughness and visual fidelity. Results with the default parameters for OBJ1 included models of high precision but with different problems concerning visual quality. Mesh produced with VSfM had holes that could not be closed, AMP and FZA produced meshes with over-simplified surfaces eliminating characteristics of less than 1 mm size and the RCP model was not complete because the web-based software was not able to exclude noise coming from texture similarities with the background. The commercial software required less processing time -comparable between them-, but number of points and mesh triangles were varying. P4D produced the densest results.

Processing with similar software parameters for OBJ2 resulted in meshes of both high metric quality and visual fidelity. Although, processing times were vastly different. The free solution was not able to fully reconstruct the scene. AMP again resulted to an over-simplified surface; P4D and FZA resulted in more accurate surfaces but with remaining noise; RCP resulted in a surface with the highest fidelity and no holes or any over-simplified geometries. Processing with RCP lasted approx. 10 hrs. producing a mesh of 5 million triangles, but no more processing details can be extracted from the web-based software.

In both cases P4D required an extra re-run of the dense matching and meshing steps (indicated with * in the below tables) for masking of images to apply and noise to be removed, since no other tools are provided to remove noise between successive steps. This resulted in an extra 1:44:38 and 1:03:57 of photogrammetric processing time for OBJ1 and OBJ2 respectively (for the first step including noise).

Fig. 1: Photogrammetric textured models of OBJ1 produced with VSfM, AMP, P4D, FZA (from left to right).

Table 2: Image-based modeling results OBJ1

	VSfM	AMP	P4D	FZA
Sparse				
Aligned	50/50	50/50	50/50	50/50
Proc. time	0:02:03	0:38:19	0:03:08	0:26:36
Tie points	4,375	252,033	213,695	52,744
Proj. RMSE		0.588 px	0.277 px	0.593 px
Dense				
Proc. time	05:40:25	00:36:52	00:36:09	00:23:15
RMSE CP	0.37 mm	0.40 mm	0.25 mm	0.49 mm
Point count	1,487,938	513,583	5,420,234	2,474,443
Filtered	308677	513094	524932	256982
Mesh				
Proc. time	00:02:16	00:00:38	00:01:36	00:00:44
Face count	505,820	491,464	2,259,158	45,665
Quality	medium	medium	medium	medium
Texture				
Proc. time	00:06:45	00:04:52	00:08:30	00:03:32
Quality	high	high	high	high
Total time	5:51:29	1:20:41	0:49:23*	0:54:07

Fig. 2: Photogrammetric models of OBJ2 produced with AMP (left) and P4D (right).

Fig. 3: Photogrammetric models of OBJ2 produced with FZA (left) and RCP (right).

Table 3: Image-based modeling results OBJ2

	VSfM	AMP	P4D	FZA
Sparse				
Matching	0:05:36	0:02:23	0:01:51	0:07:59
Alignment	0:01:13	0:01:22	0:07:10	0:15:05
Tie points	50097	119532	765793	88,130
Projections	263829	439328	2214926	
Proj. RMSE		1.686 px	0.167 px	1.592 px
Dense cloud				
Proc. time		0:46:26	0:23:31	8:16:22
Scale errors		0.64	0.64	0.00
Point count		9108791	2510221	5876497
Mesh				
Proc.time		0:05:30	0:01:06	0:09:34
Face count		1500000	1436396	1808629
Quality		medium	high	high
Texture				
Proc. time		0:04:13	0:03:39	0:04:25
Quality		high	high	high
Total time		0:59:54	0:37:17*	8:53:25

Comparisons were performed between meshes, revealing RMS differences to capturing distance ratio of approx. 1‰ and average differences of 0.4 mm for OBJ1 and RMS differences to capturing distance ratio of approx. 0.3-1‰ and average differences of 1mm – 2mm for OBJ2. Overall roughness levels did not differ on meshes produced with different software for both objects.

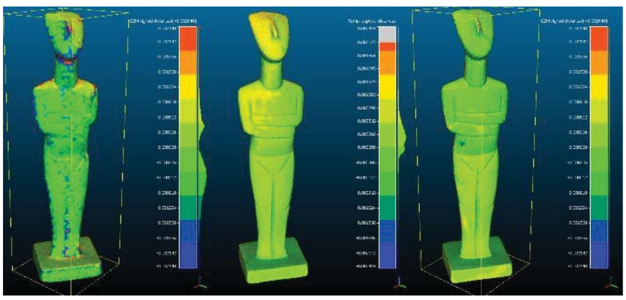

Fig. 4: OBJ1 mesh distances using as ground truth the AMP mesh (from left to right VSfM, P4D, FZA).

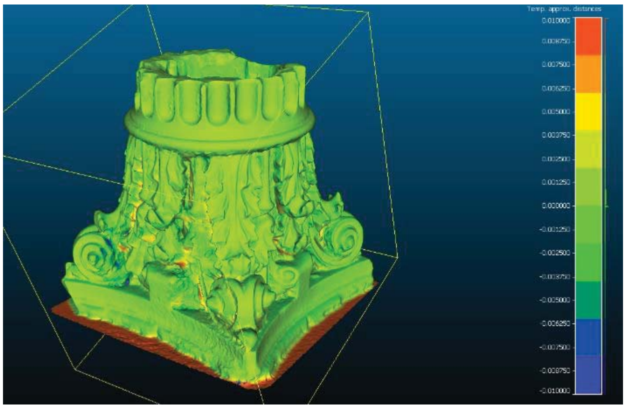

Fig. 5: distanced between AMP and P4D meshes for OB2 (max. distances shown 1 cm).

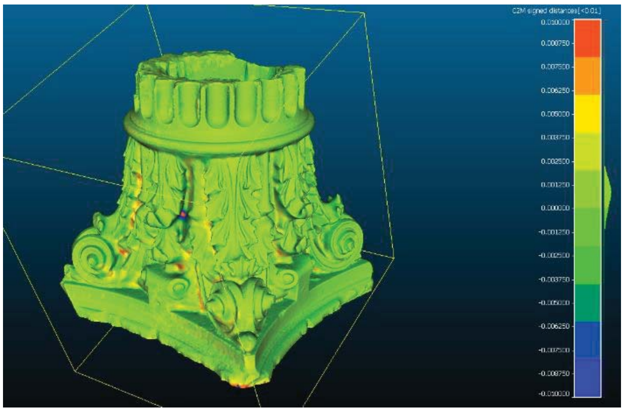

Fig. 6: distances between P4D and RCP meshes for OBJ2 (max. distances shown 1 cm).

Comparisons were also executed for the inner calibration parameters calculated during photogrammetric processing, revealing that each commercial software uses different approaches to simulate the distortions of images, despite utilizing similar pinhole models to simulate cameras. But pre-processing the results are potentially interchangeable.

Table 4: Calibration parameters calculated though SfM photogrammetric commercial software OBJ2.

	AMP	P4D	FZA
PW [mm]	0.0042	0.0042	0.0042
PH [mm]	0.0042	0.0042	0.0042
F [mm]	34.647	34.594	35.000
XP [mm]	4,344.00	4,355.00	4328.758
YP [mm]	2,896.00	2,937.41	2892.884
R1	0.000001873	-0.003263810	-0.011831200
R2	-0.000000097	0.129772000	0.181260780
R3	0.000000000	-0.145158000	-0.240987282
T1	-0.000017905	0.001582740	
T2	0.000010732	0.000864361	
T3	-0.000078854		
T4	-0.000000109		

III. SCANNING TESTS

A. Data Acquisition

For the scanning session of the two objects were used one small laser scanner, FARO Focus3D X 330, one handheld triangulation scanner, FARO Freestyle and a new handheld structured (infrared) light scanner, STONEX F6 [24]. Data acquisitions were performed under same light conditions; in order to cover the complete geometry of the objects and using scales for scaling and control of results. The scan distances were approximately 1 m, translating to 0.1-0.2 mm resolution/capturing point densities according to the manufacturers' specifications for all scanners

B. Processing

Registration, denoising, further processing and meshing was performed with the software provided or suggested by the manufacturers. For OBJ1 no model was constructed since the small scanners did not provide point clouds with enough density and the handheld scanners resulted in point clouds not correctly registered and with large amounts of noise that could not be removed neither manually nor automatically.

C. Results

Table 5: Scanning results OBJ2.

	STONEX F6	**FARO Focus3D X 330**	**FARO Freestyle**
Price	€ 13,000	€ 25,000	€ 10,000
Acquisition duration	0:02:16	1:30:56	0:10:40
Registration duration	0:05:08	0:14:35	
Denoising duration	2:25:30	0:08:39	0:00:10
Meshing duration	0:01:23	0:04:01	0:01:27
Total duration	2:34:17	1:58:11	0:12:17
Cloud points	20,928,219	1,289,032	435,053
Mesh triangles	6,350,223	6,488,395	1,950,836
Quality	very high	very high	low

The F6 and Focus3D X 330 scanners produced similar very high geometric accuracy and visual quality results in comparable times, with F6 having the easiest to use software. Freestyle produced low quality results and is better to be evaluated for the rapid mapping of scenes that have lower accuracy and lower resolution requirements than large-scale heritage object digitization.

Comparisons were performed between meshes, which showed geometrical differences of 1.8 mm RMS (0.00 mm average) or 4‰ RMS error adjusted to distance between F6 and Focus3D X 330. Meshes did not require decimation to be compared as were of similar densities. Surfaces had similar roughness and were not over-simplified. Products of scanning techniques could not fully resolve the issues regarding occlusions despite efforts on opposite direction.

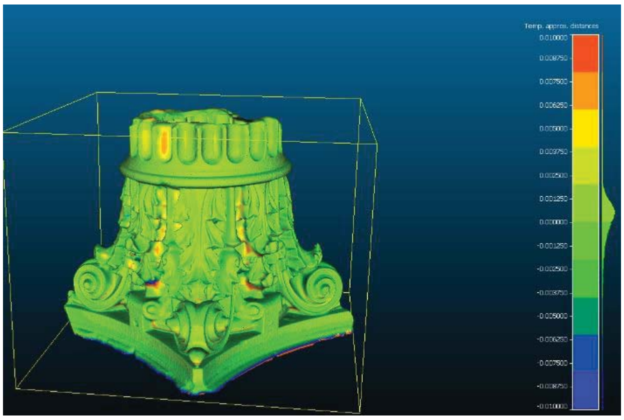

Fig. 7: Distances between F6 and Focus3Dmeshes for OBJ2 (max. distances shown 1 cm).

IV. FURTHER COMPARISONS

For OBJ2 more metric comparisons could be completed using the very high quality meshes from the scanners as ground truth to compare the photogrammetric models regarding metric accuracy, roughness and fidelity. The F6 and Focus3D X 330 scanners produced better results regarding roughness than photogrammetric systems based on SfM approach for OBJ2 but did not retrieve good color results despite prior color balancing. Differences between scanning and photogrammetric models ranged between 0.2 - 1 mm on average and 1 - 3 mm RMS. Main differences between meshes produces with photogrammetric and scanning techniques were observed at parts of the column capital that were occluded due to its complex geometry.

Table 6: Mean/RMS [mm] mesh distances comparing SfM and scanning modeling approaches for OBJ2.

	P4D	FZA	RCP	SF6	Focus
AMP	0.33 /0.89	0.50 /1.30	0.34 /0.89	0.20 /1.05	0.34/ 1.23
P4D		1.14 /1.56	1.02 /1.96	0.73 /2.61	0.21/ 1.55
FZA			0.69 /2.20	0.95 /2.41	0.90/ 1.55
RCPh				0.45 /2.42	1.21/ 3.00
SF6					0.00/ 1.85

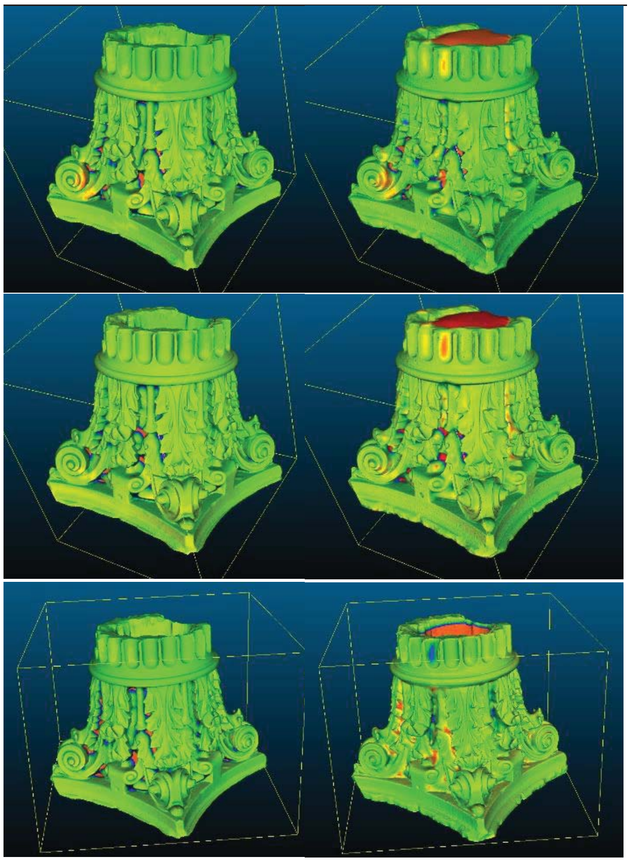

Fig. 8: Comparisons between AMP(top), P4D(middle), RCP(bottom) - F6(left) and Focus3D(right) OBJ2.

V. CONCLUSIONS

The presented research paper carries out a selective comparison on the state-of-the-art SfM approach image-based-modeling software and portable scanners for large-scale heritage digitization. As expected, challenges occur from the different nature of heritage objects, with volume, shape, texture and materials playing an important role on the decision-making for the acquisition and processing workflows. Occlusions caused by complex geometries can usually be tackled by image-based methods, but other problematic surfaces may require various combinations of documentation techniques. Taking into consideration the GSD, resolution of produced textures and accuracy of each method, photogrammetric results of OBJ1 were precise enough to produce orthophotos, be printed or replicated at least in a 1:1 scale. Finally, regarding the OBJ2, also considering comparisons with scanning-produced meshes, the results can be reproduced at large scales up to 1:10.

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