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LOW-COST 3D TECHNIQUES FOR REAL SCULPTURAL TWINS IN THE MUSEUM DOMAIN

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ABSTRACT:

The contribution presented is part of a broader study of Cultural Heritage valorisation, defining a workflow for creating full-scale copies of statues using non-contact acquisition tools and 3D printing to enable tactile enjoyment. The research presents an experiment using low-cost active and passive tools to acquire a statuary element in the Ostia Antica Park in Rome. The paper describes a testing process of such instruments, evaluating their performance from a metrological point of view. Furthermore, the experimentation verifies the morphological reliability of different copies of the original, obtained sequentially with different production processes and materials, to validate the production process of statuary copy. The scale of the case study is small and suitable for applying different survey approaches and comparing them towards the definition of a possible working protocol for massive low-cost artefacts 3D acquisition.

1. INTRODUCTION

The contribution presented here is part of a broader study of Cultural Heritage valorisation, defining a workflow for creating full-scale copies of statues using non-contact acquisition tools and 3D printing to enable tactile enjoyment. The research aims to supply operational solutions that can be applied in the conservation of Cultural Heritage field, responding to the current Italian regulatory framework for protecting original artefacts. In fact, different from the past, the Code of Cultural Heritage, Art 107, paragraph 2 of Legislative Decree 42/2004 (https://www.gazzettaufficiale.it/eli/id/2005/07/02/05A06424/s), prevents the use of traditional "direct contact" techniques on original works for the creation of cast replicas. This requires the identification of new solutions that exploit the increasingly common non-contact acquisition solutions.

Nowadays, research has identified solutions for acquiring and creating copies by exploiting the potential of 3D printing through a process that goes from real to real via exclusively digital processes. The first experiments have highlighted the capacity to generate several products consistent with the originals.

Within this framework, the general objective of this contribution is to validate a process of 3D acquisition with low-cost instruments and the 3D physical creation of replicas, comparing virtual and physical copies[1]. In detail, it foresees a metrological analysis of different digital twins obtained by several active and passive survey techniques to verify the single 3D acquisition reliability. Besides, an accurate geometrical comparison between the original case study and the replicas allows for verifying the precision of the physical copy and evaluating the results concerning the different production processes and materials. All the experiments reported in the paper will help define a new protocol for applying low-cost 3D acquisition and prototyping techniques in the sculptural domain

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2. STATE OF THE ART

The 3D digital survey of statuary complexes is a field of research that dates back more than twenty years and cannot be summarised into a brief state-of-the-art conference article. Aware of this, the authors propose only a few meaningful research works helpful in understanding the experimentation described below. Surveying experiments on statues have marked a fundamental step in developing active and passive non-contact surveying techniques for Cultural Heritage. In Italy, several survey campaigns in the early 2000s tested the potential of range-based acquisition tools for the first time (Levoy et al., 2000; Bernardini et al., 2002; Fontana et al., 2002; Guidi et al., 2004). These experiments allowed for defining the 3D acquisition pipeline, preparing for their extensive application in the Cultural Heritage domain (Bernardini and Rushmeier, 2002; Godin et al., 2002).

Why did the first experiments focus mainly, but not exclusively, on statuary complexes? The reasons are referred to several factors. Firstly, statues define a formal complexity in space that is difficult to survey. The use of contact acquisition instruments is often not applicable to limit the introduction of potential causes of degradation on the external surface. In the early 2000s, photogrammetric techniques could still extract a limited number of homologous points in space from pairs of frames, providing a simplified version of complex free-form surfaces (Grün et al., 2002). The application of range-based tools was then the only way to acquire complex free-form shapes in space. Indeed, some early discussions and experiments on the potential of using images to build 3D models (Curless, 2000) led in the first five years of the 2000s to the definitive development of Visual Structure from Motion techniques (Szeliski and Kang, 1993) capable of rendering complex 3D artefacts. They opened up some early comparisons between active and passive systems for small artefacts (Remondino et al., 2005), bringing image-matching techniques to be an effective alternative to range-based systems (Remondino et al., 2014). These experiments have also made it possible to implement and refine an acquisition process that is now well established and applied at different scales in multiple fields of Cultural Heritage applications.

Besides the formal complexity, a second reason for these first experiments is to be found in the privileged survey condition given by the size of the artefacts. Statues often present a reduced scale compared to the architectural scale while preserving a considerable variation in scale between overall size and individual details. This condition made it possible to introduce real-time acquisition modes around the objects (Rusinkiewicz et al., 2002). In addition, it allowed exploiting better the high-resolution range maps of systems with a reduced work volume (Gaiani et al., 2005), opening up several developments in the multi-resolution domain even at larger scales up to urban models (Guidi et al., 2006).

Finally, statues pose the dual issue of material and surface finish, two characteristic elements that only sometimes define an ideal acquisition condition for active and passive optical instruments. The former suffers from optically non-cooperative materials (Mathys et al., 2015) or back-scattering problems (Guidi et al., 2009). Besides, the latter is strongly constrained by external light conditions, material conservation conditions, surface patinas, and the level of light reflection (Nicolae et al., 2014).

All these boundary conditions define a complex but comprehensive research framework, which motivates the many experiments in the field of statuary. Over the last two decades, surveying techniques have changed thanks to developments in the instrumental field and implementations of digital data management (Georgopoulos and Stathopoulou, 2017).

The vision towards the definition of low-cost surveying methods has appeared since the early 2000s (Rocchini et al., 2002). Over the decades, technological development has made it possible to reduce hardware systems' size by optimizing optical and digital aspects (Bi et al., 2021). Range-based tools have shown a crucial step forward through the introduction of sensors capable of sampling the gestures of people or movements of cars in real-time (Mankoff and Russo, 2013), face drivers detection (Peláez et al., 2014), opening up some experiments in the architectural field (Ravanelli et al., 2017).

A small insight should also be devoted to introducing Lidar systems integrated with computer vision algorithms in some devices, such as IPADs and iPhones of the latest generation. Although these are very powerful and versatile tools, early experiments showed how they had been created mainly to support other tools, such as Augmented Reality (Luetzenburg et al., 2021; Wang et al., 2021). On the image-matching side, it is essential to highlight the increasingly optimized use of uncalibrated cameras mounted on smartphones for defining reliable complex 3D models (Russo et al., 2019), as well as the application of spherical images to analyse complex environments (Prizeman and Barazzetti, 2021). The numerous experiments focused on low-cost systems for the 3D acquisition of small archaeological and statuary artefacts (Kersten and Lindstaedt, 2012; Calantropio et al., 2018), highlighting considerable interest in the domain.

A final examination focuses on the purpose of surveys in the statuary domain. Twenty years ago, surveys mainly started with the dual purpose of testing tools and methodologies and proposing the first virtual replicas of artworks. In recent years, well-defined methodologies with increasingly accessible 3D systems have made it possible to plan massive 3D acquisition campaigns of entire museum collections, building accurate databases of digital twins (Guidi et al., 2015). These can be used for virtual analysis and conservation or visualization in Augmented Reality, Mixed Reality, and Virtual Reality. In parallel, prototyping techniques have also seen considerable development, making it possible to produce physical copies of 3D models with high reliability and low cost (Balletti et al., 2017). The physical reproduction of digital twins is a resource for the definition of material models on which to perform formal analyses, introduce physical substitutions, or initiate those contact study operations not permitted in original works.

Within this development framework, the article's research has a twofold purpose. On the one hand, it proposes a metrological comparison between different low-cost 3D acquisition tools. The aim here is to verify whether it is possible to systematically plan the use of low-cost systems in museums for the mass acquisition of statuary complexes of small dimensions. On the other hand, methodological verification through comparing different physical replicas from the same data source is suggested. In this case, the level of simplification of the copy will be assessed according to material and production technique, validating the overall process and identifying the best method of construction of the physical copies.

3. CASE STUDY

The Ostia Antica Archaeological Park represents one of the primary traces of Roman architectural culture in the territory of the city of Rome.

The park covers a total area of approximately 150 hectares and is, together with Pompeii, the most significant archaeological site on the planet (Figure 1). The currently visible city arose as a fortified encampment (Castrum) during the 4th century B.C. It was discovered to control and defend the neighbouring coastal strip. Within the site of the Castrum that has now been discovered, it is possible to recognize the dwellings, places of worship, and leisure, as well as a considerable amount of decorative apparatus and statuary that adorned the various architectural structures.

Figure 1. Territorial framework of the Ostia Antica area

Among the artefacts found during the excavations and currently housed in the Museum connected to the park (Antiquarium room), the contribution focused on a marble head of a statue named "Eros stringing the bow". It has been used as a case study for its limited size and the presence of different surface finishes helpful in validating the entire process.

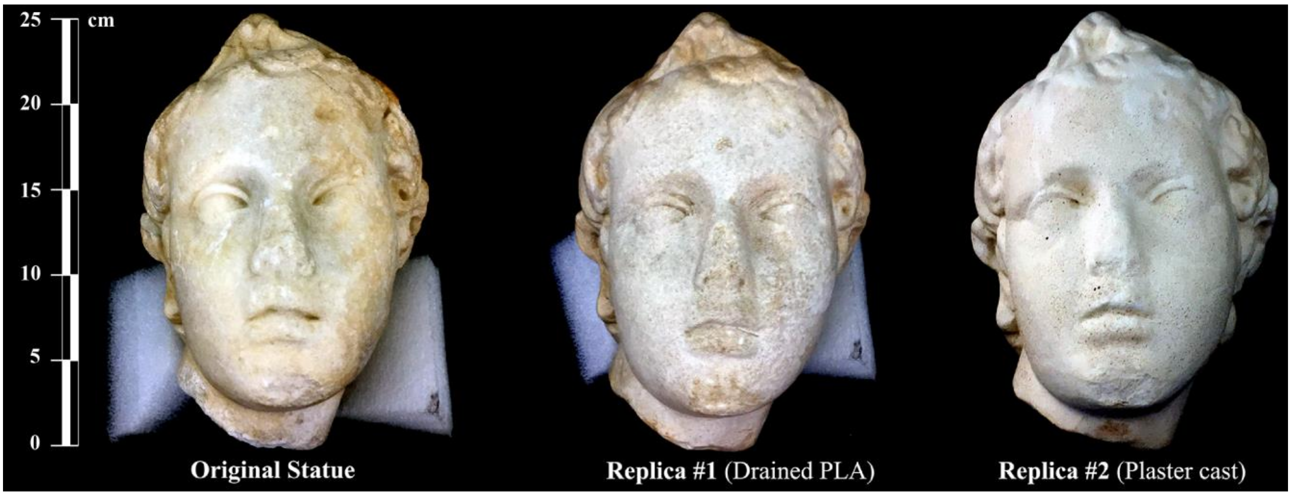


Figure 2. Case study of the Roman head (left), the first PLA copy (centre) and the second concrete casting copy (right)

Specifically, the marble head is 250 x 192 x 175 mm and appears in an excellent state of preservation. Mostly the surfaces appear smooth, but some cracks and fractures with rough surfaces help assess the detail acquisition potential of the measuring instruments used.
In the first phase, the original head was subjected to detailed scanning with a Structured Light Laser (iReal 2S, Scantech), sampling the external surface with a 0.2 mm resolution step and defining a mesh surface. It was used to prototype a model using a filament printer with Polylactic Acid (PLA) material. The choice of the less precise filament printer over technologies capable of producing better copies was made because, in the current state of technology, filament printers are the only possible solution for producing large copies. In addition, the filament printer is a young technology but the least time-consuming and least expensive solution to date, and therefore potentially usable for the reproduction of big statues. Once the PLA copy was obtained, it was first subjected to the application of a layer of manual bleaching with resin and calcium carbonate. This passage helped eliminate the layers of the printing process. In the end, a contact mould with silicone resin was applied to the replica. Once dried, it formed the basis for creating copies by casting cement and marble powder. This process thus allowed the creation of two copies with different tactile and perceptive characteristics (Figure 2).

4. METHODOLOGY

4.1 Data acquisition

The experimentation was developed in two different stages. The first used the original head of the statue as a case study. Then, multiple non-contact 3D acquisition methodologies were applied (Table 1) to compare the obtained results from the metrological point of view. The second, on the contrary, was based on applying a single accurate range-based 3D acquisition tool (iReal 2S) to acquire different physical copies of the original statue. This phase allowed the validation of the physical translation process of the digital twin, comparing the results according to the different materials and production techniques (Figure 3). The acquisition phase occurred in two different stages: outside and inside the Museum. The following premise justifies this choice. First, the authors know that the different external conditions may affect the data quality, reducing the reliability of the following metrological comparison.
Nevertheless, they preferred to identify the ideal acquisition set for each instrument to obtain the best possible result for each chosen instrument, considering the easy portability of the artefact. In addition, the change in the working context made it possible to replicate an authentic museum experience and test the operational practices, verifying their feasibility.

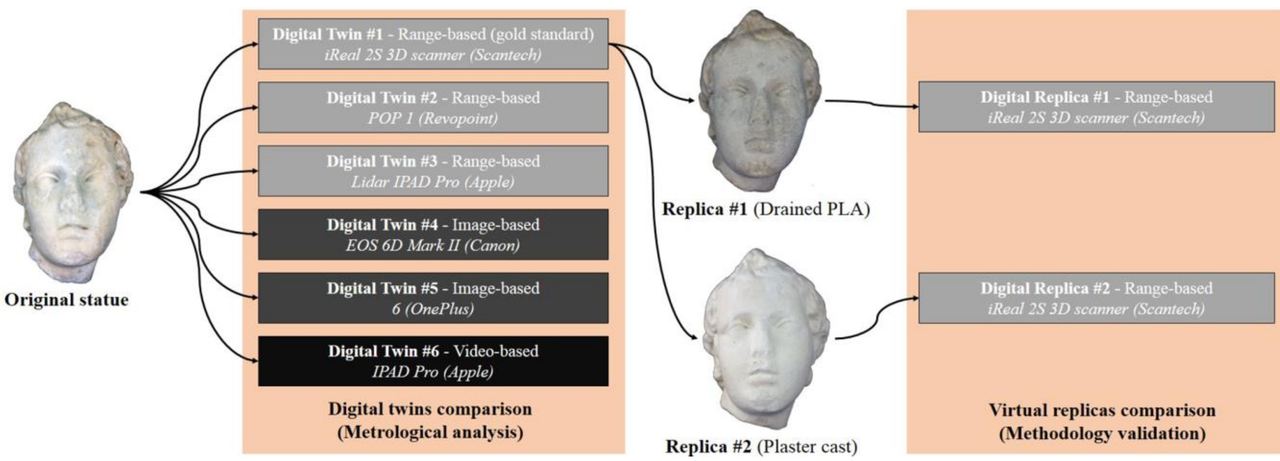


Figure 3. Methodological workflow of the experimentation.

Figure 4. External acquisition set with reflex (on the top) and IPAD (on the bottom).

In addition, no particular acquisition set with diffuse and controlled lighting was planned for the specific experimentation, defining a context similar to the non-ideal acquisition, which can be found in a museum environment. All these choices are based on the transportability of the statuary, which is only sometimes possible due to logistics, size, and weight.

Specifically, the acquisitions with an SLR camera (EOS 6D Mark II, Canon) and a smartphone (OnePlus 6) took place outdoors in non-direct light conditions. The statue has been positioned on a table. The photogrammetric blocks have been distributed at different heights around the original statue with short baselines and a 50 cm working distance. (Figure 4)

The same set was also used to capture the video with the IPAD Pro (Apple) and experiment with the Lidar instrument, testing different working distances and configurations (Table 1). The low resolution obtained from the Lidar did not allow for acceptable results (Figure 5), justifying the previous research on the topic (Luetzenburg et al., 2021; Wang et al., 2021).

The second set of range maps acquisition was planned inside the Antiquarium for logistical simplicity of the sockets required to power both PC and 3D laser scanners. Besides, the indoor conditions prevented the possible interference of the ambient light with the light projection of the active optical systems. The artificial light in the room, consisting of a sequence of spotlights placed at a considerable height, ensured a distributed but not excessively strong light projected on the artefacts.

The two different range-based instruments based on infrared fringe projection (iReal 2S Body Laser Scanner 3D, Scantech; POP 3D, Revopoint) were applied in the following configuration.

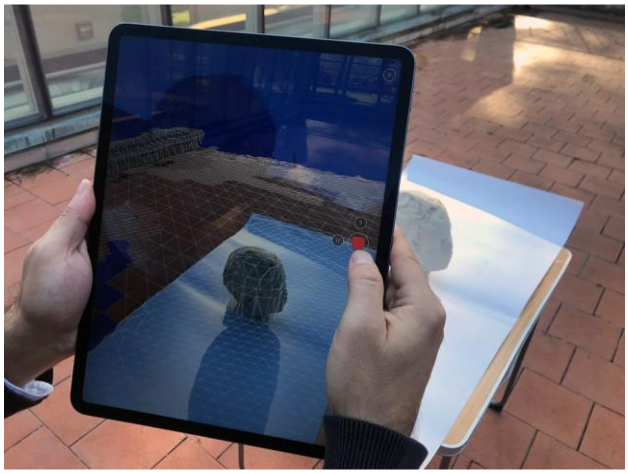


Figure 5. Lidar acquisition preview.

The original head was placed on a turntable with continuous rotation, while the instruments were fixed in different positions, sampling the entire surface (Table 1).

Figure 6. Indoor acquisition set with roundtable: on the top POP 3D scanner, on the bottom iReal 2S scanner.

The second step was devoted to acquiring the physical replicas of the original statue. Both the artefacts (in PLA or cast print) were placed on the turntable and scanned with the iReal 3D laser scanner. It was considered the most accurate and, therefore, the one that can most reliably show any volume and surface variations between the different replicas (Figure 8).

Instruments	EOS 6D Mark II	OnePlus 6	Video IPAD	Lidar IPAD	POP 3D	iReal 2S
CCD	6240x4160	4608 x 3456	3840 x 2160	/	/	/
Sensor dim. (mm)	35.9 x 24	5.68 x 4.27	17.3 x 13	/	/	/
Pixel dim. (μm)	5.75	1.22	/	/	/	/
Diaphragm aperture	f/8	f/1.7	f/1.8	f/1.8	/	/
Focal length (mm)	50	4	14	26	/	/
Working Distance (mm)	500	500	1000	1000	200	300
# Images	38	49	845	/	/	/
GSD* // Res. (mm)	0.06	0.15	0.32	40	0.15	0.2
Accuracy (mm)	/	/	/	/	0.3	0.1

* Mean value considering the 3D shape and a plane passing through the barycentre of the statue box

Table 1. Main data of the instruments and the acquisition set-up.

4.2 Data processing

All acquired data were processed in different 3D data environments. The images acquired with the SLR and smartphone were oriented within the software Metashape (Agisoft), building respective dense point clouds and textured polygonal models. The sequence of frames captured with the IPAD Pro was instead processed within the 3DF software Zephyr (3DFlow). The result obtained from the video sequence, although presenting elements of interest considering the short time of acquisition (less than 30 seconds), was not considered of sufficient quality and detail to be considered in the comparison phase (Figure 7).

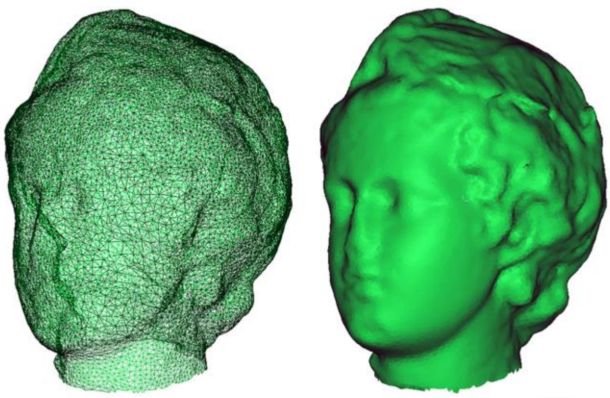


Figure 7. Mesh and shaded model obtained by video sequence.

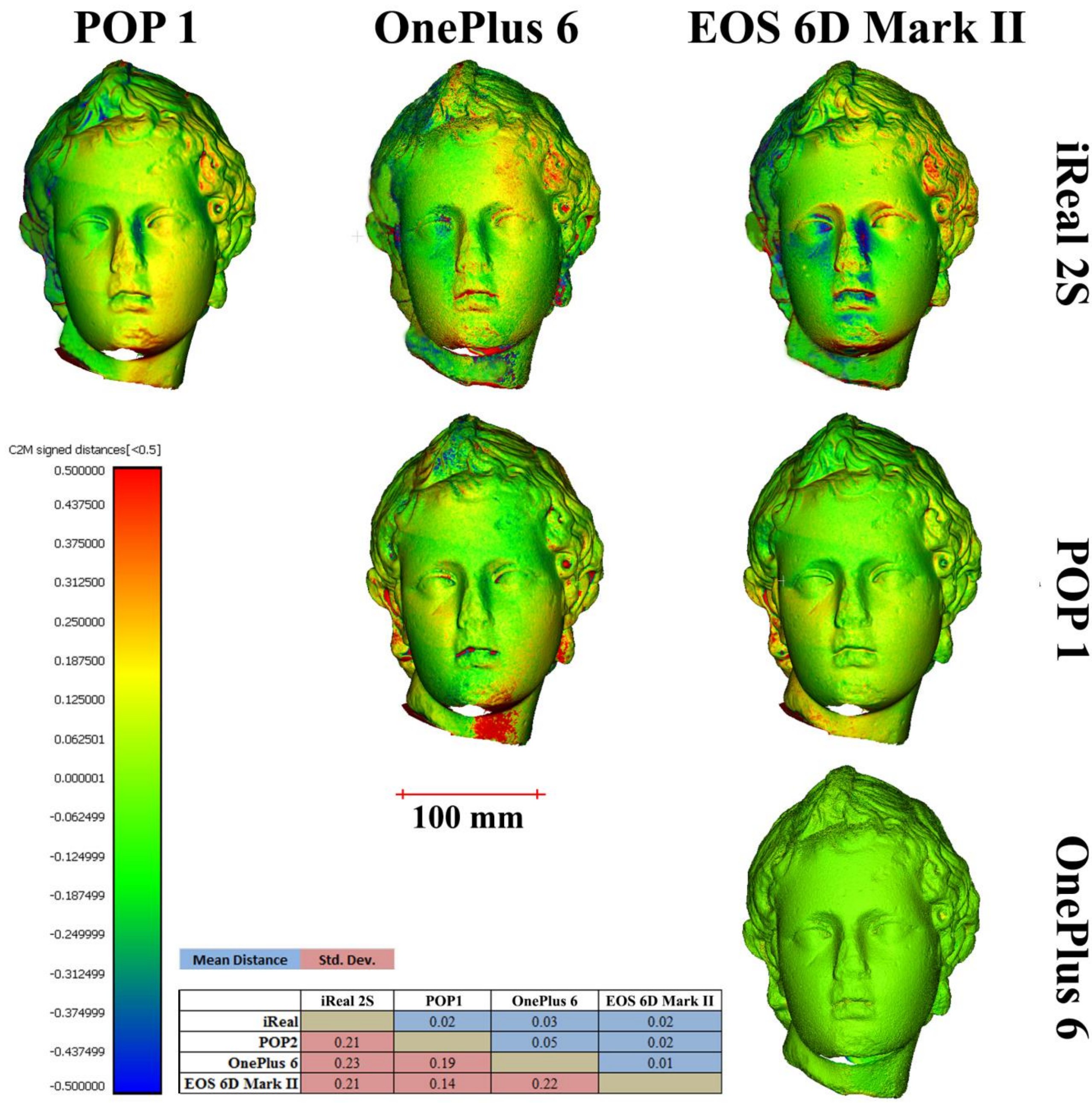
All models obtained through image matching were scaled using the model obtained from the iReal 2S 3D laser scanner as a reference. Due to its specific instrumental characteristics, it was considered the metric reference for the entire experiment. The other range-based data were processed in their proprietary software, using automatic feature recognition through the camera when orienting the range maps. All range-based and image-based polygonal models were used without smoothing or filtering data to verify the raw instrumental response to the case study. The different models were imported into the CloudCompare software, where the scaling process (for image-based data) and roto-translation took place to analyse the deviations between the individual models. Each model was used at its native resolution, avoiding the introduction of decimation processes that could affect the model's shape in any way, thus preserving the detail of that specific 3D system.

4.3 Data comparison

Some initial considerations can be made after the metrological comparison between the different twin models (Figure 8). Generally, the deviations between the different models are minimal concerning the instruments' capacities and insignificant for prototyping purposes. The photogrammetric output confirmed the highly reliable technique in terms of surveying and modelling process. The image-based models are accurate both in terms of geometric and radiometric aspects. However, the specific surface characteristics of the case study lead to a slightly noisy surface, defined by small ripples that do not exist on the surface of the original statue. This condition can be partially overcome by smoothing the surface, thus introducing a variation from the acquired data. In terms of deviation from the gold standard, both the model obtained from the SLR camera and the smartphone showed high reliability, although some minor differences related to the different characteristics of the camera (Figure 8). Finally, as far as the low-cost range-based system (POP 3D) is concerned, the deviation shows good accuracy and reliability of the geometric combined with a discrete acquisition speed. Furthermore, both 3D systems defined a smooth digital surface of the original statue, thus preserving the surface treatment's appearance.

However, it is interesting to observe that some parts of the statue, such as the nose and eyes, show a significant deviation in data restitution between the active and passive systems.

As far as the comparison between the actual case study and its replicas, it is highlighted how the various production steps introduce geometric variations. The gold standard model of the original statue obtained by the iReal 2S instrument is compared with the virtual models of the PLA and casting replicas acquired with the same instrument, showing an increasing distance between the original shapes. However, these differences are not significant in perceptual terms, except in correspondence with the specific surface variation of the statue (the eyes, the mouth, the hairs); on the other hand, they highlight the high production quality and reliability of both techniques. Therefore, the comparison shows how it is possible to obtain reliable copies quickly and with limited costs, overcoming the legal limits imposed on creating contact copies of the original.



	iReal 2S	POP1	OnePlus 6	EOS 6D Mark II
iReal		0.02	0.03	0.02
POP2	0.21		0.05	0.02
OnePlus 6	0.23	0.19		0.01
EOS 6D Mark II	0.21	0.14	0.22	

Figure 8. Deviation maps obtained by comparing the different virtual models obtained with the active and passive acquisition tools. Below is the table with the average distance and standard deviation between the models.

5. CONCLUSIONS

The research presents an experiment using low-cost active and passive instruments to acquire a statuary element in the Ostia Antica Park in Rome. The research aims to test such instruments' use and evaluate their performance from a metrological point of view. Besides, it assesses their massive application in constructing virtual repositories of digital copies of entire museum collections or contained in archaeological areas. Furthermore, the experimentation aims to test the morphological reliability of different copies of the original, obtained sequentially with different production processes and different materials. It allows validating a production process of statuary copies. The small size of the case study and its transportability made it possible to configure different acquisition set-ups, obtaining comparable results between different active and passive low costs 3D acquisition methodologies.

From an instrumental point of view, using Lidar as a 3D acquisition tool for small complex surfaces proved insufficient. The grid of sampling points and the low accuracy of the data did not allow for acceptable results at this scale. This type of instrument, although promising, cannot be applicable in the statuary field at this size and level of detail. Similarly, video sequences make it possible to reduce acquisition times drastically, but the data quality still needs to be improved in order to compare it with other acquisition techniques. On the other hand, as far as the other instruments are concerned, the analysis revealed the high reliability of all the systems, with minimal deviations concerning the gold standard reference

model. These deviations are coherent with the instrument capacities but insignificant in the prototyping process.
Photogrammetry presents greater flexibility in terms of the context of use but poses the constraint of controlled and uniform light over the entire surface of the statue. It also does not allow the results to be verified in real-time. Furthermore, it should be emphasized that, at a perceptual level, the generated surfaces are noisy, particularly for all the smooth areas, which can be quickly resolved through the application of smoothing filters, and it is, in any case, irrelevant for the subsequent prototyping phases.
On the other hand, the range-based systems analysed showed a considerable speed of use. However, the constraint of being powered by electricity makes them impractical for outdoor applications unless an uninterruptible power supply is applied. In addition, the impact of external environmental conditions on the acquisition of range-based data based on structured light should be analysed in detail.
Furthermore, the limited shooting box constraints applications to small acquisition scale unless targets are introduced. Extended surfaces may show some limitations in preserving feature recognition and the correct orientation of the instrument.
The virtual copies obtained from replicas present geometric variations mainly due to the production method but with minimal deviations. This result demonstrates the quality of a low-cost production process. In conclusion, this experiment opens the door to more extensive experiments aimed at highlighting, on the one hand, the limits of each 3D low-cost acquisition method. It is crucial to frame its specificities better concerning the types of case studies. On the other hand, it makes it possible to lay the foundations for defining a protocol for 3D acquisition and printing activities that can be replicated extensively in a museum context.

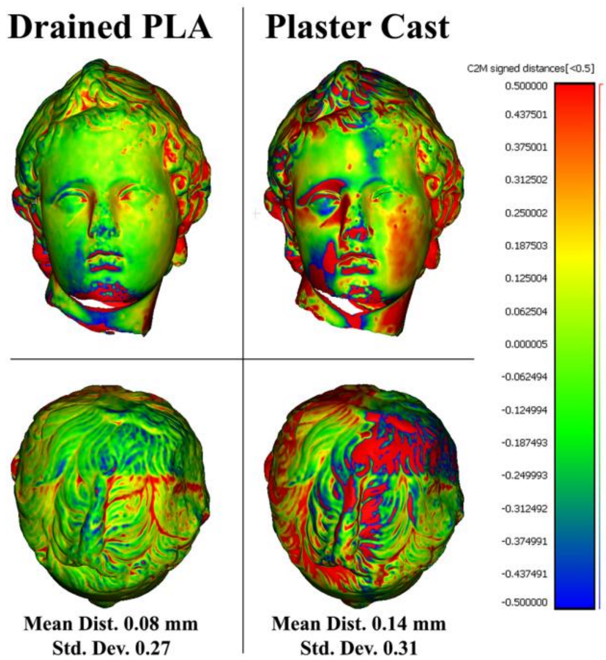


Figure 9. Deviation maps comparing the virtual reference model (iReal 2S) obtained by the 3D scan of the original statue with the two replicas obtained sequentially in the prototyping process using different techniques and materials. The deviations are mainly referred to the specific production steps.

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