An Exploratory Study on the Application of Reverse Engineering in the Field of Small Archaeological Artefacts

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ABSTRACT

In Italy's artistic heritage, there are numerous small artefacts that are rich in details usually invisible to the naked eye. In the last decade, the need to document and create digital archives of cultural heritage has triggered research on the application of well-known reverse engineering techniques. Despite the applications in the field of virtual heritage, the 3D digitalization and reconstruction of small archaeological artefacts remains an open issue due to their small dimensions and handling constraints. In this context, this paper presents a methodology to compare the performance of two different techniques for 3D digitalization, one using a triangulation laser scanner and one using Structure from Motion (SfM) photogrammetry. The methodology is based on a QFD approach to identify and quantitatively evaluate the differences between the achieved 3D models. It has been applied to the famous limestone sculpture called "Venus of Frasassi". The main advantages and limits of both techniques are discussed with a focus on their ability to allow the identification of hidden shape features.

Keywords: Reverse Engineering, QFD, Archaeology, Virtual Heritage.
DOI: https://doi.org/10.14733/cadaps.2019.1209-1226

1 INTRODUCTION

In the recent decades, in the context of cultural heritage there has been an explosion of innovation related to the application of 3D acquisition technologies, rapid prototyping, computer rendering and virtual prototyping techniques to support the development and fruition of digital documentation [14].

Some of the most important advances in Reverse Engineering techniques (e.g., evolution of the hardware and software tools, achievements in 3D reconstruction algorithms) are reported in [6]. However, there is no methodology to identify which is the best technology in a particular situation in which different needs and scales can be found (e.g., archaeology artefacts, sites, architecture and monuments, and paintings and sculptures). As demonstrated by a literature overview [15], the requirements to identify the best hardware and software tools and the proper procedure to digitize and reconstruct the model come from not only the inner characteristics of the artefacts (e.g., size, shape features, and material) but also from the phases through which the objects pass in their lifecycle, from discovery to conservation into a museum and from digitalization to 3D printing. Each phase is supported by different technologies (e.g., laser scanner, CAD tools, simulation software, and computation analysis tools) that can impact in different ways the understanding of objects and on the transmission of their values [3]. Figure 1 sums up the main stages of their lifecycle, considering the finding as a physical product that passes through digital processing and preservation. Consequently, an interdisciplinary approach is required to specify the digital model parameters (e.g., resolution, accuracy, dimension) and a reverse engineering procedure based on conservation, rehabilitation and use of the artefact. This lack of a methodology is particularly noticeable in regard to artefacts that, despite having small dimensions, present many particular details. In fact, depending on the purpose or context of the use of the digital model, its use requires a high level of fidelity. This obviously impacts the choice of adoptable technology, and above all affects the level of accuracy that it can reach.

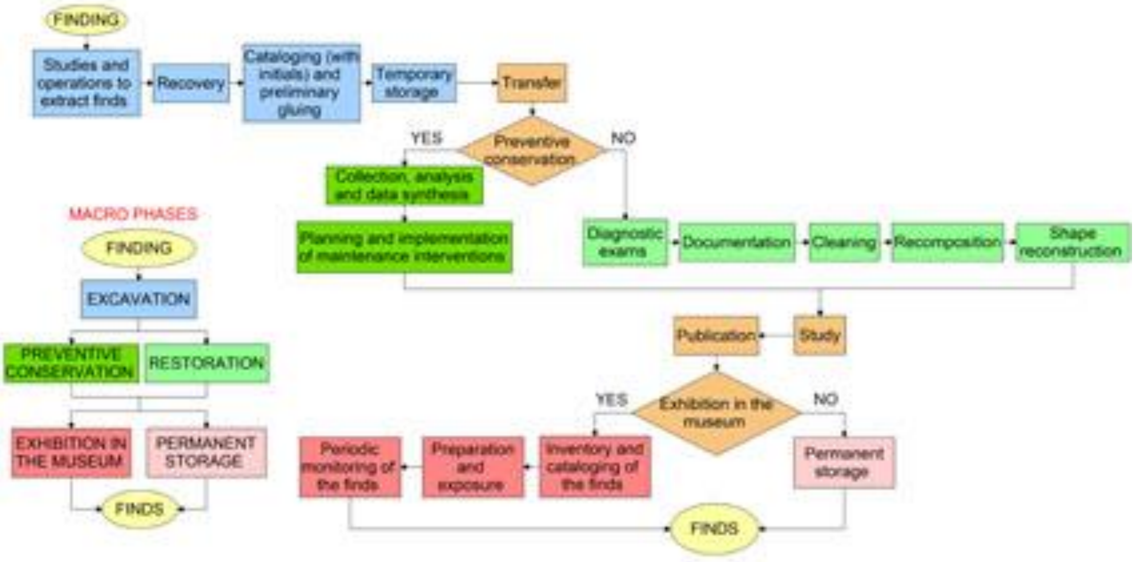


Figure 1: Life cycle of the find, from finding to museum.

In this context, this paper proposes a structured methodology to guide the choice of the best acquisition technology according to the model needs and application requirements (e.g., accuracy and precision) and to the characteristics of the acquisition process (e.g., acquisition time, post-processing time). To preliminarily validate the methodology, a case study is proposed in which two different acquisition technologies have been used, i.e., laser scanner triangulation and structure from motion SfM (based on photogrammetry), applied to a small artefact. The comparison takes into consideration the performance of the supporting hardware and software, the characteristics of the achievable 3D models enabling the overall artefact lifecycle and the whole process efficiency. Additionally, a technology comparison was conducted, with the support of a Quality Functional Deployment (QFD) approach that takes into consideration multiple operative factors [10].

What separates this research from previous works [14], [15] is the characteristics of the objects that, apart from their small dimensions, are rich in details invisible to the naked eyes, but significant for historical studies, restoration, conservation setting and, finally, digital reproduction.

Consequently, when the scope and the use of a 3D model require a very detailed rendering of these details, the model should be strictly faithful to the original object. To this end, the detailed accuracy that is required for acquisition must be very precise. However, other parameters are selected for the comparison, e.g., the inner characteristics of the objects and the requirements of the lifecycle phases. A description of the overall pipeline and related supported tools is presented to obtain a 3D final model for both cases of photogrammetry and laser scanning. In this way, further processing factors are considered to discuss the advantages and limits of each technique.

The methodology is described through the case study of a small statue named Venus of Frasassi. Tests outlined some important aspects about the highly precise laser scanning to discover hidden shape features and achieve conservation purposes. The experimental results were strongly influenced by the particular topology and material of the statue. The choice of the two compared technologies also depends on the application context and to the well-known competition between photogrammetry and laser-based acquisition techniques. However, these aspects affect the achieved values of pipeline stages duration and digital model target accuracy but not the methodology applicability. Further experimentation is necessary to validate the methodology by changing the application context, the dimension of the scanned object and the types of benchmarked technologies.

2 STATE OF THE ART

Thanks to the evolution of computer graphic methodologies, cultural heritage is enjoying great advantages in the study, representation and conservation of digital artefacts [5]. In fact, traditional methods (e.g., callipers, ruler, manual drawings, reports) do not allow the digital facsimile to be sufficiently detailed or precise or achieved in a short time compared to techniques based on 3D scanning [11], [14]. Since cultural heritage handling requires special care, acquisition protocols are much stricter than the ones required for scanning less valuable objects, as, for example, in industrial applications [14].

Some of the most important tools for cultural heritage digitalization are as follows [14]:

- Laser triangulation systems are one of the most common technologies using an active sensor. The working field of this technology is medium sized.
- Stereo-photogrammetry is one of technologies based on a passive sensor. Through a combination of some 2D images, a 3D model is obtained.
- Structured light scanners are a technology that uses one or more cameras that capture the deformation of the light pattern projected on the object. The 3D model is obtained by capturing this deformation from different points of view.
- Time of flight systems are to be preferred in the case of large volumes because the accuracy is around the order of the centimetre.

Notwithstanding, there are previous studies that have analysed medium and small objects with different tools and for different purposes [1], [9], [11], [17]. Consider the case of a fragmented terracotta statue destroyed in the Aquila earthquake [1], where the principal scope of the model was to help the experts to reconstruct the artefact and to create a physical support for the fragments. A similar situation is the case study of Michelangelo's David, where the application consists of an acquisition that was finalized to restore its support and for specific investigations [12]. The problems and requirements to consider during the acquisition campaign of many artefacts are different than previously reported [9], [17], and consequently the technologies to be employed also differ. In the literature, there are few applications that compare different technologies used for the same case study [14], [18]. Most studies do not compare technologies but integrate them in the application [2], [13].

In general, all of the technologies, as a result of acquisition, return a series of single scans that must be registered and edited. The registration is necessary because each scan has a different coordinate system, and the points refer to it [14]. After the elaboration, a 3D model can be obtained. It is a faithful and measurable digital representation of the examined object through explicit representation of its form and colour characteristics. In detail, a typical pipeline to obtain a 3D model is reported in [14], and it is summarized here below by the following passages:

1. Data registration: single scans must be aligned or registered between then in a one coordinate system. To date, this step is not completely automatic since first a manual recording must be carried out or a tracking system is used in the most advanced applications [4].
2. Data integration: there are several approaches to perform this step, which depend on how input data is assumed. The scope is the creation of a model that represents the geometry and topology of the acquired object [4].
3. Model conversion: this is one of the most important phases of the pipeline. It consists of mesh creation and decimation to obtain the 3D model of the object. As most studies have suggested, there are different methods for meshes decimation and finding the most efficiently algorithm is very difficult. Subsequently, to allow for the best diffusion of the 3D model, it is necessary for its conversion into different formats or into one of the most common universal formats [14].
4. Visualization: achieving a realistic result is a very long process because some components, e.g., light and texture, are difficult to reproduce properly despite there being many rendering techniques [14].

3 THE METHODOLOGY

The evaluation methodology is composed of six steps (Figure 2) and integrates the achievements of previous research studies [10], [14]. It starts with the selection of the most suitable technologies for the scope, depending on the subject to be acquired and the type of results to be achieved. In fact, not all available scanning technologies are suitable for all cases and for this reason a preliminary benchmark is imperative; this is also related to the subject artefact, including its material, size, and topology.

The second step includes the digitalization of the physical artefact with the selected technologies (two or three) and the application of the procedure to obtain 3D models.

The third step regards the definition of a set of evaluation metrics used for comparison of the selected technologies performance and digitalization results. Sets of evaluation metrics are as follows: acquisition and processing time, scans necessary to cover the object’s surface, and steps of the elaboration pipeline and related times. Other metrics could be the accuracy of the models, the units of measurement of 3D models and the percentage of the object’s surface coverage.

The fourth step foresees model alignment and geometric comparison; this step includes a general macroscopic comparison and an analysis of the obtained deviations. It is a critical point of the evaluated methodology. First, it starts by imposing a tentative maximum deviation value of 1 mm to find the actual maximum deviation value. In the second phase of the fourth step, some reductions of maximum deviation value are checked to better understand the differences within the analysed 3D models. The representation method is the colour map. In small objects (as per this case study) the deviation analysis focuses on areas where there are details for which the maximum acceptable deviation should be significantly reduced. In this way, it is possible to detect model areas for which more detailed analysis should be conducted. By this methodology approach, the results shown as coloured maps are very useful since they are more intuitive; however, numerical values should not be neglected.

The fifth step regards the evaluation of cross sections focused in the areas of details. Cross sections are to be made every 1 mm vertically and horizontally so they intersect the points of greatest interest to be selected. In each cross section, the distance between each technology generated profiles to be compared (always with the help of the coloured maps). In addition, the deviation values along the section can be extrapolated. Part of the fifth step is the build-up of local grid sections in the areas with significant details. The grid is made up by vertical and horizontal cross sections every 0.25 mm. At this point the deviation value can be extracted as before.

The sixth step is the definition of a repeatable digitalization, editing and validation procedure to be applied with both 3D scanning technologies and to assure the reliability of results or to choose the best technology among those being analysed.

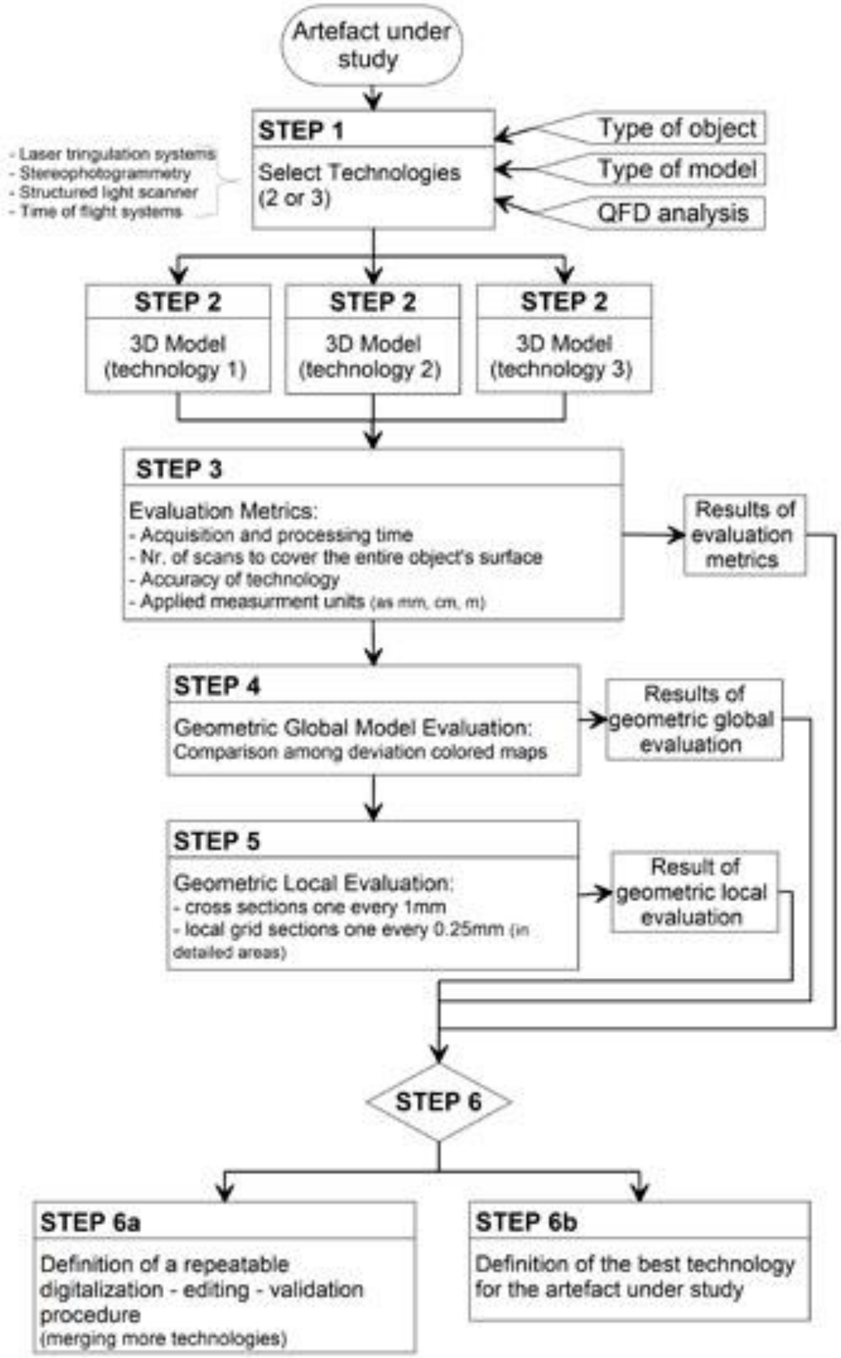


Figure 2: The methodology.

This methodology has been validated for the study of "Venere di Frasassi" (Figure 3), which is one of the most important pieces on display in the National Archaeological Museum of Marche (Ancona). The material from which this small statue (8.7 x 2.6 cm) is constructed is limestone, typical of the central area of the Frasassi clefts in the Apennines of Marche. This area is characterized by many caves with stalactites from which the statuette is supposed to have been obtained.

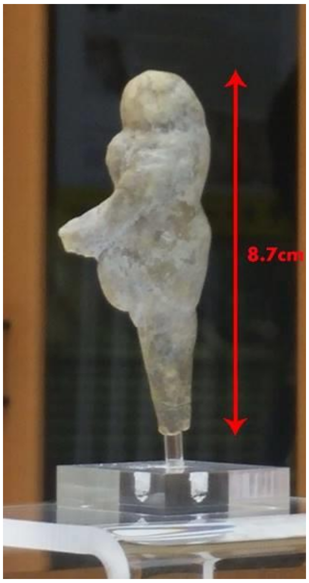


Figure 3: The Venus of Frasassi (8,7 cm).

3.1 Triangulation Laser Scanner

In cultural heritage, most artefacts are very delicate and are priceless, such that any contact should be avoided. For these reasons, in most of the applications, non-invasive optical sensors have been used. According to [16], the sensors are of two types: passive and active. Passive sensors are digital cameras; a 3D model is obtained through the 2D image (photo) and some mathematical formulas. Active sensors are laser scanners or radar, where the 3D information is directly derived from the instruments. A triangulation laser scanner is an instrument based on optical triangulation whose working principle is described in detail in [14]. It uses the following relationship Eqn. (3.1) to obtain the distance r between the laser and the illuminated points of the object:

$$r = b \tan^{-1}(\alpha + \beta) \tag{3.1}$$

where α and β are the angles, and b is the distance between the camera and the emitting laser [14].

The scheme of work is shown in Figure 4: the laser emitter projects a beam laser on the object to be scanned and at the same time a CMOS sensor (video camera) captures the light stripe [7]. The advantage of employing a laser as an emitter is the generation of a stripe with a limited and constant thickness in the large projection depth, thanks to the reduction of the divergence angle [10]. To obtain the entire object, the procedure is repeated from different points of view to cover all of the object's surface.

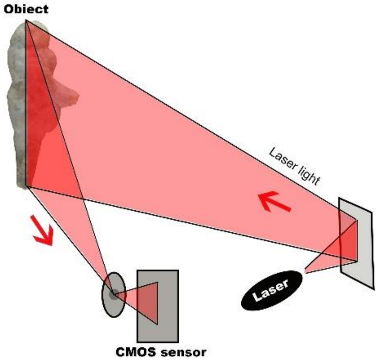


Figure 4: Laser Triangulation Working Principle.

The scanner used (a non-contact 3D digitizer: Konica Minolta Range 7) has almost completely solved the problem of the mirror surfaces through a working mode that allows for capturing data on highly reflective objects. In this way it was not necessary to perform the acquisition in controlled lighting environments, leading to an organizational streamlining and speed of execution. In addition to the scanner, a graduated turntable was used to facilitate acquisitions. For this acquisition, also due to the small size of the statuette, the 'tele' lens was used to obtain additional details. The precision of the laser scanner is 4 μm and the accuracy is ±40 μm. Given the small size of the object, the focus and the exposure were set on the automatic mode and the scanner made three passes in a single scan. The acquisition campaign lasted 1–2 hours, during which 13 scans were made together with a first alignment from the Konica Minolta software Range Viewer. The distance of acquisition was variable from 50 cm to 68 cm. The first alignment was made with the corresponding three points between two scans. In this way, a preview of the scans has been obtained to verify the surface portions acquired up to that moment. Range Viewer is not a software used for alignment, and for this reason, the scans were re-aligned with Polyworks software using the best-fit alignment, an interactive algorithm that has the scope to minimize the distance between surfaces superposed in a group of scans where the point of acquisition is unknown (Figure 5 (a)). The alignment was made using only 10 of the 13 scans, and it produced a mean standard deviation of 0.0257 mm (min 0.0198; max 0.0338). The result of the alignment of the scan was a 1.53 mln point cloud. The overlap between different scans was then reduced, obtaining a final cloud of 898 k points with a mean distance of 0.0928 mm.

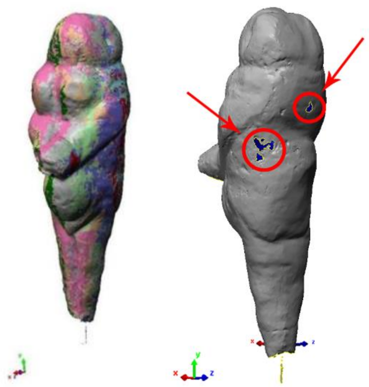


Figure 5: Results of laser scanner triangulation: (a) the overlap between the different scans after the alignment and (b) the details of the holes in the 3D model.

Ending the alignment phase and following the editing phase, a mesh model was generated in which all the holes smaller than 0.4 mm were closed. As it can be seen from Figure 5 (b) there are holes in the dimensions that show a lack of data, probably due to reflective particles present in the material.

3.2 Digitalization by Structure from Motion

Structure from motion (SfM) is a photographic technique through which three-dimensional models (3D models) are made to combine a series of photos. This technique is considered an evolution of photogrammetry because it is more automatic than the others. SfM, in the acquisition phase, needs some tools: a full frame reflex camera, a white photographic box, two lamps and a turntable [8]. In particular cases, it is also necessary to use a computer with specific software for control of the digital camera. The object to be digitized is placed on a turntable under the photographic box; the digital camera, mounted on a tripod, is in front of it (Figure 6). The photographic box is used to spread the light of the two lamps; in this way sharp shadows are not formed on the object. The turntable allows for rotation of the object between two consecutive shots, keeping the camera fixed.

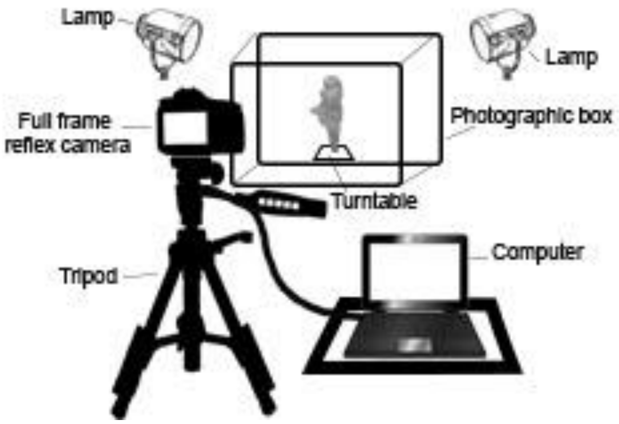


Figure 6: Instrumentation used for the photographic acquisition.

Before the acquisition phase, a schedule is required, based on the following parameters: characteristics of the camera sensor, acquisition distance, focal length, size of the object and overlap between two pictures. In the schedule, the operator needs to calculate the degrees of rotation between the two pictures, applying the formula Eqn. (3.2), that considers the above parameters:

$$\alpha = (100 - \%) \cdot 2 \cdot \arcsin\left\{ \frac{D \cdot \sqrt{(D^2 - r^2)/r^2}}{\left[(D^2 - r^2)/r^2 + 1\right] \cdot r} \right\} \tag{3.2}$$

where

ɑ = degrees of rotation between two pictures
D = distance from the object
r = radius of the object (represented in a cylindrical form)
% = percentage of overlapping between two consecutive pictures (for a small object, at least 80% is recommended)

Despite SfM being a very suitable technique for small-medium sized objects, in some cases (e.g., objects only a few centimetres in size) there may be a problem related to the depth of field;

for this reason, the focus stacking techniques is used. For each camera pose, a stack of images is made at different focus planes, which, combined, allow for obtaining the entire object in focus (Figure 7). The main problem is the short depth of field (DoF), which translates into only a small portion of the artefact being in focus.

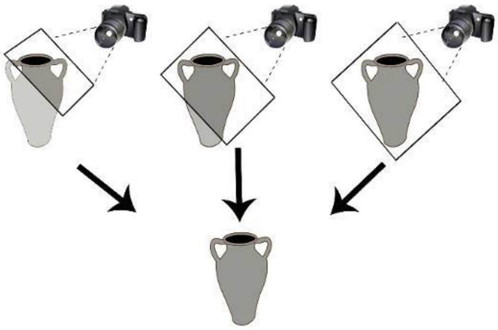


Figure 7: Movement of the focal plane during the acquisition with focus stacking [8].

The full frame reflex camera used in this case study is the Nikon D810, with 36 megapixels and equipped with a Nikkor 105 mm macro lens. The distance used for taking the pictures was 43 cm, with a focal length of 105 mm, obtaining a GSD of 0.020 mm. A total of 72 images were captured, one every 15° at three different heights, which were imported into the photogrammetric project with Agisoft Photoscan 1.1.6 software [8]. The model was built following the typical pipeline for 3D reconstruction: alignment of images [19], scaling and orientation of the model, construction of dense clouds, mesh model and final texturing. The point cloud obtainable went from 98k points at low resolution to 42 mln points at maximum resolution; the average alignment error in the point cloud of 98k was 0.674 pixels (maximum 0.722 and minimum 0.630 pixels) and 250k of projections.

4 VALIDATION

The validation process, described in the following sections, first includes a general description/comparison of the analysed technologies in terms of dimension, geometry and accuracy of obtainable results. Then, the description/discussion of the case study will follow, together with the narrative of the relevant 3D model's representation obtained in the acquisition campaign.

4.1 General Comparison of Digitalization Technologies

Laser scanner technology and SfM are both optical acquisition techniques that are reality based. The differences depend on the type of sensor:

- active sensor or range-based technology (laser scanner 3D), where the coordinates of the measured points are directly acquired; for this reason, the resulting cloud of data points are in the Cartesian reference system, including metric information;
- passive sensor or image-based technology (SfM, camera), where 3D data are extracted from images (bi-dimensional) and converted in a 3D model, therefore geo-referencing and scaling the needs of other metric information with homologous landmarks (target).

Currently, passive sensors are also able to obtain tri-dimensional digital models very accurately, similar to active sensors [16]. According to the above, SfM and image-based technology in general need an organization phase before the acquisition campaign. This phase is called "Progetto di presa". In this phase, the problem of the metric information that is not included in the 3D model obtained with the camera is considered. The objects that are acquired with SfM retain the proportions, but the scale is defined by the operator manually. For this reason, it is easy to make mistakes about the dimensions; in fact, at the beginning of this case, the dimensions of the Venus of Frasassi were wrong because it was in metres instead of in millimetres. With this approach, one must preliminarily calculate the acquisition points and decide the sequence of photos and their numbers, both in the case of large architectures and of small objects. This phase causes an increased work time and represents a disadvantage, because it requires a preliminary study that is not necessary in the laser scanner technique and because it is necessary to know the theory of "Progetto di presa". The choice of one technology or another depends on the characteristics of the relief, the object's form, the position in the space, the logistical conditions of the context and the scope of the 3D model. In fact, as was mentioned in the first paragraph, there are many types of 3D models: as aids in cataloguing in the excavation phase; for the creation of a suitable container; for transportation and/or storage in museums; for study, restoration and conservation; for the public fruition.

The requirements, such as accuracy, precision, colour, scale, and cost, have different priorities according to the kind of model. In Table 1, we have reported the weight of each requirement. In particular, we distinguish the 3D models for study and conservation in the cases of 3D models for restoration, storage, and study and the 3D models for public fruition. The requirements listed above, besides the importance they have for the model type, form the basis of the comparison between the two technologies. Elaborating on the qualitative analysis made by [7], which used four parameters, we applied the methodology of quality function deployment (QFD) to put into relation the requirements' model and the specific tools, acquisition and modelling. QFD is a customer-oriented approach to product innovation. QFD supports design teams to develop products in a structured way that relates to market demand via engineering specifications to parts specifications and to production process variables, and thus to production operations planning [10].

Requirement	*3D model for public fruition*	*3D model for study/conservation*		
		Restoration	*Storage*	*Study*
Accuracy	3	9	9	9
Precision	3	9	3	9
Scale*	3	9	3	9
Colour	9	3	3	9
Cost (factor)**	9	0	3	3
Visual fidelity	9	3	3	3
Visual performance	9	3	3	3
Value: 0 not important; 3 important; 9 very important * Scale with respect to the real object ** Incidence of cost factor in the realization of the work				

Table 1: Requirements for different kinds of models.

Table 2 reports the requirements of the model for public fruition and Table 3 shows the analysis of the same requirements of the model for study conservation. The requirements of the 3D model are reported in the lines, and they include the principal aspects that must be considered during an analysis of a model. Some requirements are strictly correlated with the consistency of the model with the object analysed, e.g., real scale, fidelity, colour, and detail level. Others refer to the digital model, e.g., the file size, colour, and procedure's consistency. The technical parameters to consider in relation with the requirements are reported in the columns.

Beside its size, it is very important that the geometry, the accuracy of the chosen technology and the need of the chromatic component and materials documentation (as seen in the above tables) are taken into account. In the case of a large indoor or outdoor site, a laser scanner is better than SfM (photogrammetry, in general) because light is easier to control.

	Tool Specifications, acquisition, modelling / 3D model requirements for study/ conservation	Importance requirements	Importance requirements %	1 Accuracy (X e Y)	2 Precision (Z)	3 Resolution (Mpx)	4 Acquisition volume	5 Acquisition distance	6 Lighting	7 Acquisition time	8 Processing time	Total assigned value (row)	Technology: Laser scanner	Technology: Photogrammetry
1	File size	1	3.7	3	3	5	5					16	3	1
2	Real Scale	3	11.1	5	5	5		3				18	5	1
3	Fidelity	4	14.8	5	5	1						11	5	3
4	Colour	5	18.5			3			5			8	1	5
5	Cost	3	11.1				3			5	5	13	5	3
6	Detail level	4	14.8	5	5	5	3	3				21	5	3
7	Time of realization	3	11.1				5			5	5	15	5	5
8	Procedure 's consistency	4	14.8					3	3	5	5	16	5	4
	Total	27	100									118		

Table 2: QFD scheme to specify the requirements of the 3D model in cases of application in virtual setup in museums.

Photogrammetry is affected by low ambient lighting, while the laser scanner is not affected by ambient lighting. The same problem occurs when there is an overexposed, backlit or strongly reflected area. Another problem regarding SfM and light is the employment of a system that creates a dynamic light condition (static light with a turn table). Theoretically, systems that create static light conditions, typical in laboratories, produce better models in the SfM and dense matching. However, these lighting conditions are difficult to obtain in the museum and, above all, in cases of valuable artefacts. Recently, these problems have been reduced due to changes of photos, filters, and tripods, but the difficulty remains. In case of small objects, refer to the case study described. Related to light problems, there is the visual rendering of the material and therefore the material itself. The material's date is a factor very important in respect to technology. The material characteristics are the chromatic data and the texture. SfM is the best technology from this point of view, but recently even laser scanners have been integrated with digital cameras for colour acquisition. Application of the colour texture on a digital model is very difficult if the camera is not integrated into the laser scanner. In the case of monochromatic surfaces and reflective surfaces, even photogrammetry presents some problems in the object's coverage.

	Tool Specifications, acquisition, modelling / 3D model requirements for study/ conservation	Importance requirements	Importance requirements %	1 Accuracy (X e Y)	2 Precision (Z)	3 Resolution (Mpx)	4 Acquisition volume	5 Acquisition distance	6 Lighting	7 Acquisition time	8 Processing time	Total assigned value (row)	Technology: Laser scanner	Technology: Photogrammetry
1	File size	3	10.0	3	3	5	5					16	3	1
2	Real Scale	5	16.7	5	5	5		3				18	5	1
3	Fidelity	5	16.7	5	5	1						11	5	3
4	Colour	2	6.7			3			5			8	1	5
5	Cost	2	6.7				3			5	5	13	5	3
6	Detail level	5	16.7	5	5	5	3	3				21	5	3
7	Time of realization	3	10.0				5			5	5	15	5	5
8	Procedure 's consistency	5	16.7					3	3	5	5	16	5	4
	Total	30	100									118		

Table 3: QFD scheme to specify the requirements of the 3D model in cases of restoration and conservation purposes.

Another important factor of comparison is time, understood as the sum of the time required for the acquisition and time for processing. Time for acquisition depends on the operator's experience. This was especially evident in the case of SfM. When acquiring by this technology, the configuration of the camera is manual, and for this reason the photos may not be focused and then the procedure must be carried out again. When using laser scanner, if the setting requires manual configuration, the scanner will not scan if the object is out of focus. Time for acquisition is the same for both technologies. Instead, time for processing in the SfM is longer than for laser scanner, about three times longer. The reason is the time required to edit the photos because sometimes the light and colours are not correct. Operation that requires more time remains the alignment to obtain the mesh. The factor time is very variable because it needs to be considered also whether human errors that may occur in the acquisition phase will reappear in the processing phase.

The final aspect to be analysed, in this general comparison, is the cost of the instruments. The instruments necessary for each technology are listed in the above paragraphs, where the technologies are described. In the laser scanner technology, the cost is four times higher than SfM. This aspect has to be viewed in the light of the factors analysed in this section, especially time and acquisition errors, and not only from the point of view of the cost of the tools.

4.2 Comparison Between the Achieved 3D Models

The comparison between the SfM model and laser scanner model was made with Polyworks software with the IMInspect module.

The laser scanner model was chosen as the reference. Its system of reference is the point where the scanner is placed, but for the comparison, it was more convenient comfortable to change this system and put it at the end of the legs of the statue. This setting change was imported into the models in the software and then we proceeded to align the SfM model. If the models are far away, as it was in the present case, a first manual point pairs alignment is necessary. Then, a best-fit alignment is applied to make small corrections. It is actually a surface-based alignment tool that iteratively transforms the position and orientation of a data object (SfM model) to minimize the deviations of the data points with respect to the surface of a reference object (laser scanner model).

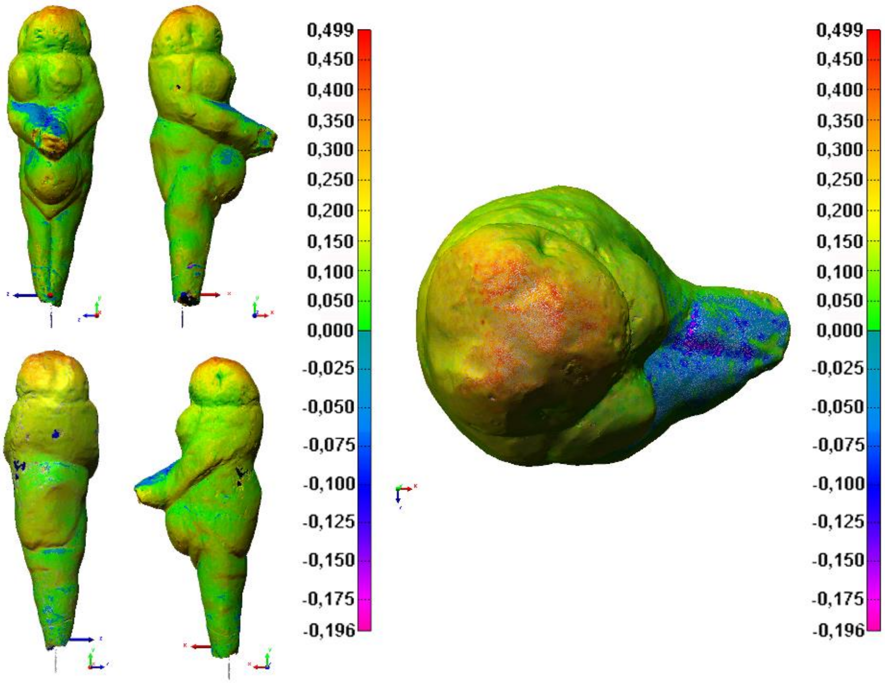


Figure 8: Difference model: (a) Laser scanner-SFM (maximum distance 0.5 mm), (b) View from above.

At this point, a comparison was made considering the value of the deviation between the two models. The offsets (differences) were represented as colour-code-visualizations. Figure 8 (a) shows the difference between the model, where the maximum distance is 0.5 mm. There are many areas in which the models are coincident (i.e., colour: light blue), e.g., the arms, any part of the back and mouth, and any areas in which there are differences (colour: red), such as the top of the head (Figure 8 (b)). This analysis highlights that the two models are almost completely equal; the maximum deviation value is 0.499 mm and the minimum value is −0.196 mm.

Once demonstrating that the two models were comparable, the research focused on the detailed study of the Venus head because it is the part less distinguishable and visible to the naked eye. In this part, we went to increase the maximum distance accepted and tests were carried out with different values: 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm. Only the case carried out with 0.4 mm was accepted because, in the other cases, the values obtained were higher than the set limit. The results of this second analysis are shown in Figure 9.

The top of the head has the maximum distance (i.e., the area in red in Figure 9), while the face and the sides are closer (i.e., parts coloured in yellow and green). A cross section along the plane XY of both models was made to draw the two profiles and their deviation (Figure 10).

The face of "Venus of Frasassi" obtained by the laser scanner digitalization revealed many surprises that the SfM did not show or that the laser scanner digitalization showed better detailed;

the model produced by the 3D scanner made easier the recognition of some details that were not seen in the point cloud from photogrammetry. The mouth (**Error! Reference source not found.**) is the most important element in the small statue; it humanizes the object and makes it more charming. This element was not seen in the SfM model because the superimposed colour confused the researcher's eyes. The same researcher immediately noticed the mouth in the 3D scanned model where only the geometry and topology were represented with high detail and resolution. Consequently, the necessity to separate colour from geometry is fundamental, as demonstrated in this particular case study, where the principal scope of the technologies is the digitalization for studies.

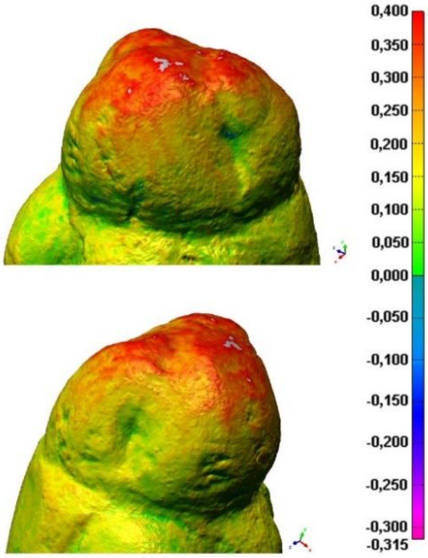


Figure 9: Detail of the head, difference model: Laser scanner-SfM (max. dev. 0.4 mm).

The mouth is the part about which we have carried out a further analysis, being the smallest element. We proceeded with the creation of cross sections in the vertical and horizontal directions in the mouth. The aim was to view the deviation in these points. Three vertical and horizontal cross sections were chosen from the sections made every 1 mm only in the head (Figure 12 (a)). Zooming into the mouth, one can see the two profiles that are almost perfectly coincident. In particular, in these points, the minimum values of deviation are present in each of three sections at −0.047 mm (Figure 12 (b)).

In addition to the above sections, a grid was also made in the mouth area (Figure 13). Cross sections were made in the vertical and horizontal direction every 0.25 mm, and for each one, the deviation between the two models was computed. Seven horizontal sections and 13 vertical sections were made. The results show that the two models are very similar; in fact, the minimum deviation value between all cross sections is −0.049 mm. The minimum, maximum and average deviation values in the horizontal and vertical sections are shown in the figures below. As can be seen, the trend of the deviation's values for both the vertical and horizontal sections is similar. This result shows how much the two 3D models are comparable.

5 CONCLUSIONS

This work demonstrates an evaluation methodology to compare two different digitalization technologies and the necessary pipeline to reconstruct the 3D model of small archaeological artefacts. The results of the study point out the weakness of SfM in case requiring a very accurate and realistic scaled model, and non-expert personnel to carry out the acquisitions. However, the best solution is the integration of both technologies, as SfM is good to achieve the artefact facsimile to interact with visitors through novel human-computer interfaces, while the 3D scanner is a key technology for the velocity of acquisition and the high resolution of the point cloud.

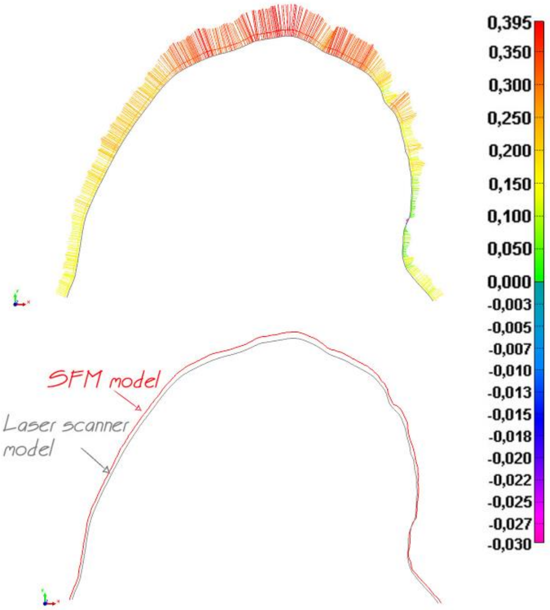


Figure 10: Cross section along the plane XY of the head, and deviation of the two profiles.

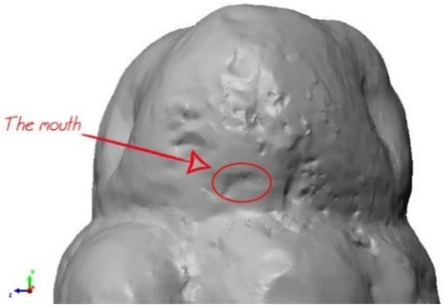


Figure 11: Face of the Venus.

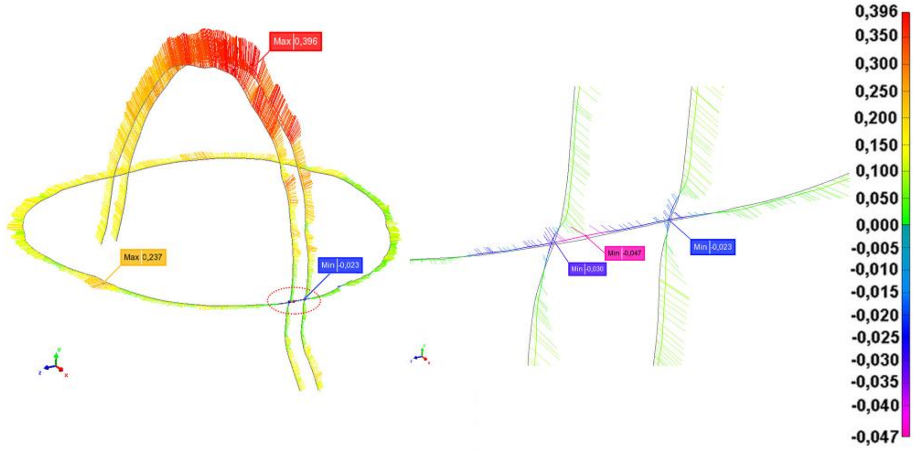


Figure 12: Cross section corresponding to the mouth, and detail of the mouth.

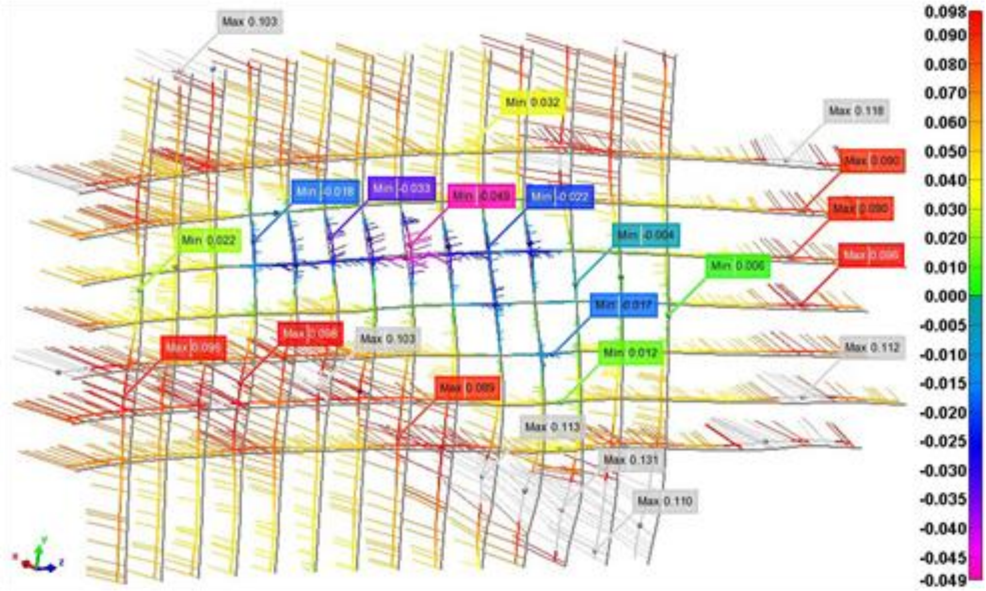
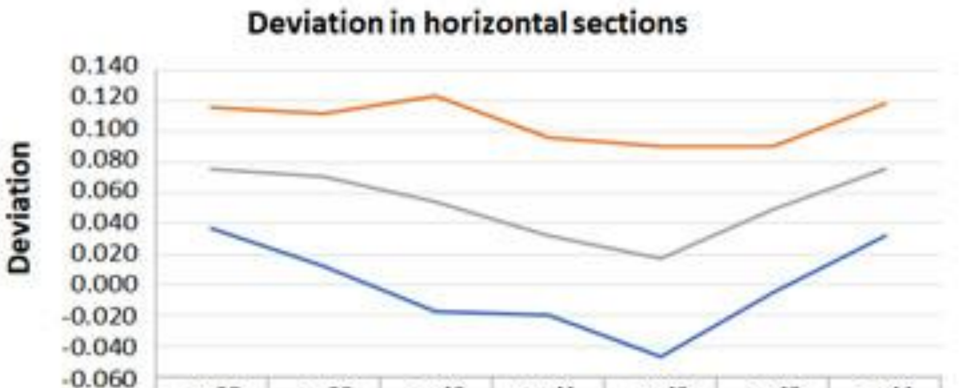


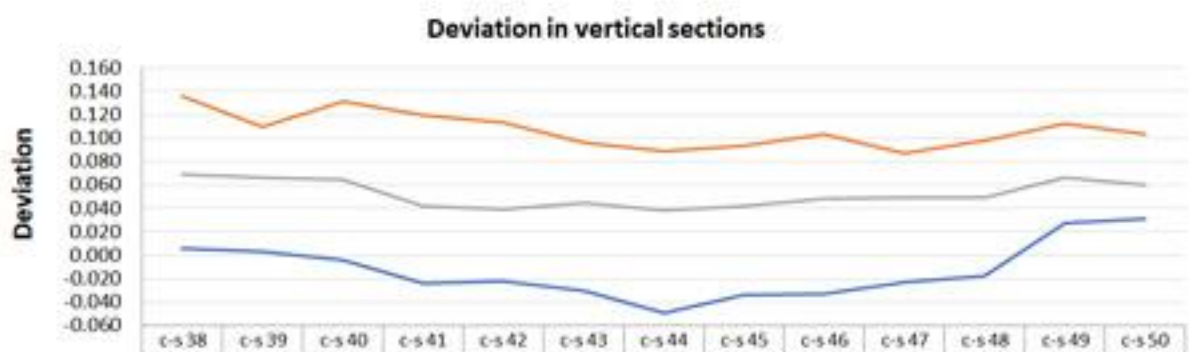
Figure 13: Grid of sections in the mouth area.



	c-s 38 (y=71)	c-s 39 (y=71.25)	c-s 40 (y=71.5)	c-s 41 (y=71.75)	c-s 42 (y=72)	c-s 43 (y=72.25)	c-s 44 (y=72.5)
dev. min	0.037	0.012	-0.017	-0.020	-0.047	-0.005	0.032
dev. max	0.116	0.112	0.123	0.096	0.090	0.090	0.118
dev. media	0.076	0.071	0.054	0.032	0.017	0.049	0.076

Figure 14: Deviation in horizontal sections.

This study and the resulting discoveries show the increased need to scan cultural heritage objects, both to preserve them and to enhance them with innovative applications. Moreover, the comparison between the two technologies has allowed us to understand the importance of a preliminary comparative analysis to evaluate the pros and cons in the specific case that is going to be analysed. Future work will be focused on the collection of more digital artefacts to validate the methodology and on the definition of combined techniques to superimpose models that differ in accuracy, resolution, and provided information about colours and textures.



	c-s 38 (z=1.25)	c-s 39 (z=1)	c-s 40 (z=0.75)	c-s 41 (z=0.5)	c-s 42 (z=0.25)	c-s 43 (z=0)	c-s 44 (z=-0.25)	c-s 45 (z=-0.5)	c-s 46 (z=-0.75)	c-s 47 (z=-1)	c-s 48 (z=-1.25)	c-s 49 (z=-1.5)	c-s 50 (z=-1.75)
dev. min	0.006	0.003	-0.004	-0.024	-0.022	-0.030	-0.049	-0.034	-0.033	-0.023	-0.018	0.028	0.031
dev. max	0.136	0.110	0.131	0.120	0.113	0.096	0.089	0.093	0.103	0.087	0.098	0.112	0.103
dev. media	0.069	0.066	0.065	0.042	0.039	0.045	0.038	0.042	0.048	0.049	0.049	0.066	0.060

Figure 15: Deviation in vertical sections.

6 ACKNOWLEDGEMENTS

Thanks to the National Archaeological Museum of Marche and its director Nicoletta Frapiccini and the Polo Museale Marche and its director Peter Aufreiter. We thank the staff and Prof. Clini of the Dept. of Civil and Building Engineering and Architecture of Polytechnic University of Marche for useful insights.

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