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Massive 3D digitization of sculptures: Methodological approaches for improving efficiency

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Abstract. This paper describes a methodology for efficient massive 3D digitization of ancient sculptures under the scope of IU-Uffizi project. The project is sponsored by Indiana University (USA) with the technical support of Politecnico di Milano and the advice of a scientific committee of experts in the fields of art history and archaeology. The project aims at digitizing 1250 ancient sculptures in the "Uffizi museum", Pitti Palace", "Boboli Gardens" and a storage facility inside Villa Corsini in Castello near Florence. The authors have experienced a variety of different issues in the museum, including working with different lighting conditions, the placements of sculptures at difficult places for shooting images, inaccessible height and different ways for posing camera on the scene in an environment where the use of drones is prohibited. To solve such issues, specific technical choices were needed to reduce the digitization time and costs while maintaining a high coherence between the physical artefact and its digital counterpart. These technical solutions are being discussed, in a context where the purpose is to massively digitize complex objects in their original setting by minimizing the impact on the museum. Furthermore, several methodologies are being discussed to improve the efficiency of digitization regarding image capturing, 3D model creation, scaling and mesh editing.

1. Introduction

The digital era has led us to witness a *revolution of relevancy*, based on understanding of its effect and the boundaries of its use [1]. Nowadays, digital applications are used to promote the museum's heritage in several fields such as education, promotion, advertising and research. The IU-Uffizi Project was developed by the museum in an effort to highlight an important collection of ancient Greek and Roman sculpture, which is often not given the attention to its merits by the visitors of the Uffizi, who understandably, are mostly interested in seeing the masterpieces of painters such as Giotto, Leonardo and Botticelli. Therefore, the project confronts two challenges: (i) amplifying the visibility and comprehensibility of the sculptural heritage for museum visitors and (ii) using digital publication on the Internet to make the sculptures better known to students, scholars, and the general public wherever they may live. To deal with these challenges in operational terms, one must select appropriate digital solution and methodology, so that 3D modeling not only becomes attraction but also a tool for analyses.

This paper describes a complete pipeline and several technical choices to achieve the final goal for which the Indiana University-Uffizi Project was developed: to respect the museum's needs, the contemporary visitor's desire for engagement, and to increase knowledge and spread cultural awareness beyond the confines of the museum itself by utilizing the Internet. The results of two years activities are already showing that people are more eager to visit the archaeological collection and are paying more attention to its masterpieces. Visitors have also had the chance to talk directly to the scientists engaged in the project thanks to several public lectures and meetings held at the museum and open to the general public, in which various aspects of the project were discussed. The project has also prepared a website on which all the sculptures modeled can be viewed. It is expected that the website will be open to the public shortly. Meanwhile, the Uffizi is in the process of embedding the project's newly created 3D models onto its own publicly available website.

2. Developments of digital technologies in cultural heritage

The advancements in digital photography [2]–[5] have led to a whole new role of image-based 3D imaging in several areas, including cultural heritage documentation. Based on the international experiences starting from the late 1990's to the early 2000's [6]–[9], several projects are being developed, especially at the European level, to improve technologies and methodologies for systematic digitization of the museum contents.

Starting from the EPOCH network of excellence (2004-2008) [10][11], several areas have been identified for concentrating research efforts to achieve an efficient and sustainable application of digital technologies to archaeological research and the presentation of cultural information in museums and historical sites. In 2008, the 3DCOFORM project was started to develop some of the main tools to create reality-based digital models of sculptures and museum objects in general. The process uses a series of well-established processing steps for each museum object of interest i.e. the 3D acquisition, the processing of the texturized model, its visualization and the creation of metadata with which to describe the different descriptive and technical aspects of the model [12]. This method of the digitization process was supported by several tools developed during that project, such as: (i) the InHand Scanner, a manual device to quickly acquire the 3D shape of a museum object, (ii) the MultiView Dome to capture the visual appearance of an object such as color and reflectivity, (iii) the well-known software in the public domain Meshlab, which is now being widely used in the production and post-production of 3D models originating from 3D acquisition [13] and (v) the Ingestion tool to load the metadata of a 3D model on the EUROPEANA platform.

During the past five years, some initiatives for massive 3D digitization of complete collections of archeological artifacts have been started worldwide. The 3DICONS (2012-2015) has provided EUROPEANA with over 3000 objects, environments, buildings and specially digitized archaeological sites, which include for example the entire contents of the Civic Archaeological Museum of Milan [14].The Cultlab3D was developed in Germany by the Fraunhofer Institute for Computer Graphics Research IGD, which is an automated digitization system for small museum artefacts [15]. It is based on a conveyor belt and a series of devices positioned along the path, which capture both the shape and the visual appearance of the object under examination, significantly reducing the digitization time of a museum piece. The 3D Petrie Museum project, developed by University College London (UCL), dealt with the systematic digitization of the Egyptian Petrie art in London and networking of the relevant 3D models [16]. It was similar to the Smithsonian 3D project developed by Smithsonian Institute [17].

3. Materials and Methods

3.1. Principal technique

Even though in some cases laser scanning was used (scaling of models for example, see section 4.1.), but the main 3D capturing technique used in the IU Uffizi project is Structure from Motion (SfM) / Image Matching (IM) photogrammetry, which allows to acquire both the geometrical and surface texture of the captured objects. Even though the photogrammetric process is highly automatic, the results can still be affected by the photographic quality of the images, the proper distribution of camera locations in space around the artifact being surveyed and skills of the post-processing operator.

The 3D acquisition pipeline based on active devices [18], requires a considerable amount of manual work in some of these steps, with particular emphasis on alignment, mesh and texture editing. Contrarily, the SFM based approach, is fully automatic after acquiring the images in correct sequence. The output of this process is a textured 3D mesh for which a moderate amount of editing might still be needed, but the extent of the editing work is smaller to that for scanned models. Even though high resolution can be achieved by using triangulation based laser scanning, the texture still has to be re-created from images on a 3D scanned model. This process requires to orient all of the texturing pictures by the 3D model orientation and projecting them on the portions of mesh that are visible at the corresponding point of view of images. Finally, the overlapped images are blended in terms of exposure and color temperature. As a result, generating a texturized model from a mesh obtained from an active device is much more time consuming than the automatically generated texturized model from SFM [19]. Furthermore, compared to scanning, much less equipment is required for photogrammetry, which can easily be carried to reach the sculptures irrespective of their size and placement. Triangulation based 3D scanning devices are not be suitable for capturing the whole sculpture geometry because of their different sizes and cannot be moved because the museum is open for public display.

3.2. Photographic Devices

A careful selection of the camera and mounted lenses is fundamental for achieving optical image quality for photogrammetry. The camera used for most of the photogrammetric survey in this project was a mirrorless Sony α6000 with a 24.3 megapixel APS-C CMOS sensor and E-mount lenses. Depending on the camera object distance (the placement of sculptures in the museum) and the surface quality of the surveyed objects, two different lenses were used: a Zeiss Sonnar 24mm f/1.8 and a Zeiss Touit 12mm f/2.8 Lens. Thanks to the combination of one of the widest fields of view in APS-C format, the latter lens was especially useful for digitizing sculptures near the wall which will be explained further in section 4.2.

All of the images for the outdoor sculptures were captured with natural light. Same approach was adopted for the sculptures placed inside the gallery or museum rooms, wherever possible, the use of artificial lighting was avoided. In situations, especially inside the rooms with no windows, where enough natural light was not present, standard photographic illuminators with controlled color temperature were used. In addition, for acquiring the back sides of the sculptures, close to the walls, a HVL-RL1 LED ring light was used. It is a device designed for video recording, therefore it is a continuous illuminator and not a flash. This particular feature is useful for guaranteeing the proper functionality of the autofocus function.

3.3. 3D capturing procedures

The illumination in the rooms and galleries of the museum was a mixture of artificial spotlights and the natural lights from the windows. Other sculptures placed outside in “Loggia dei lanzi” and “Boboli Garden” were illuminated by the uniform natural lighting. Based on different lighting conditions, four different approaches were used to adjust the white balance: (i) an Automatic White Balance (AWB) mode was used when the sculpture was illuminated by a uniform mixture of natural and artificial light (in the rooms with a lot of windows) or uniformly illuminated by the natural light (sculptures placed outdoors); (ii) a White Balance set for artificial lighting was used for the sculptures that were predominantly illuminated by the artificial lighting; (iii) for the sculptures illuminated mainly by the exterior light coming from the windows, the White Balance was set for the exterior light temperature and (iv) for the sculptures that cannot be moved and are placed in a position where the light temperature is extremely different on the back side than the front side, a color-checking panel was placed in the scene to adjust the color temperature on raw images before processing.

As no zoom lenses were used in this project, therefore the focal length remained the same for all sets of images in order to avoid a calibration parameter for focal length. Operating mode was set to be “Automatic” with Aperture priority, because distortions are very much influenced by the aperture size. The f-value was chosen based on the desired depth of field. In any situation even with very low lighting conditions, the f-value was not set to be more than 5.6.

The sensitivity level (ISO) was set to be as low as possible based on the lighting conditions in order to avoid noise grains on the images, which in turn can reduce the accuracy of 3D measurement. However, for less illuminated objects, the ISO value was set to be higher than minimum to avoid any movement blurring due to long exposure time while capturing images without a tripod. For all of the shootings in this project, the “ISO” value was not set to be higher than 1000 for any lighting condition, instead a tripod was used wherever necessary to avoid increasing the "ISO" value. For outdoor shooting in normal daylight where generally enough light is available, a minimum ISO value was used to obtain minimal grains in the photos.

As, the software used for aligning images can process only "jpeg" format of images (which allow a maximum dynamic range of 8 bits per channel), therefore to achieve a higher dynamic range, "raw" format of images was selected for shooting which allowed us to work on the color or exposure corrections in post processing phase without losing useful information.

3.4. Data processing and post processing

"Agisoft Photoscan", which is a semiautomatic software package, was used for orienting the images to create dense cloud and meshes. The camera orientation and the internal calibration are made automatically in this software, allowing a little interaction to the user. The software implements image orientation and mesh generation through SFM and dense multi-view stereo-matching algorithms.There are several kind of objects of different shape, measures and materials in the museum, therefore several potentially critical situations may occur. Since the aim of the project is to produce a high number of models in a short period of time, one of the main factor was to identify the best pipeline with a reasonable tradeoff between processing time and accuracy. Several test on different types of objects were performed for deciding a reasonable setting of the meshing parameters.

For post-processing, i.e. mesh/texture editing, model orientation, possible fine-scaling and model analysis, different open source and commercial software packages were used. These include: (i) Autodesk meshmixer; Pixologic ZBrush; InnovMetric Polyworks for Mesh editing; (ii) Pixologic ZBrush and Adobe Photoshop 3D for texture editing and (iii) MeshLab and CloudCompare for the final model analysis and orientation. In Figure 1 some examples of the final results are shown. The project is still in progress with more than 300 3D models already produced, with an average rate higher than 20 new 3D models per month, which is compliant with the massive 3D digitization operation needed in the framework of this project.

(a) (b) (c)

Figure 1. Some examples of final models with high resolution texture (16 mega pixel); (a) Laocoön and his sons In the Uffizi gallery; (b) Horse Buontalenti in the basement of Uffizi gallery; (c) Ancient Medici lion in loggia dei Lanzi.

4. Technical choices

4.1. Scaling

In the beginning, for first year of the project, scaling has been done by following the standard procedure of photogrammetry, i.e. by placing several targets in space around the object to be digitized. Even though accurate scaling can be achieved by utilizing this method, but it is very time consuming in terms of placing the targets in the scene and manually measuring precise distances between them. Therefore, this scaling approach was changed later on in the project. To speed up the scaling procedure, we have used FARO Focus 3D laser scanner, working on the principle of range sensing based on phase shift detection. As the points cloud generated by a laser scanner has an absolute scale: each point represents the actual position of corresponding point in space with some measurement uncertainty, the model generated by the photogrammetric process (which has a relative scale) can be scaled by aligning it with the points cloud from laser scanning.

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To determine the accuracy of this method of scaling, a 2m tall sculpture of Demeter was digitized by photogrammetry and scaled by using physical targets, which resulted in a scaling error of less than 0.5mm (Figure 2a). Correspondingly, a single scan was made for a part of the same sculpture (front part in this case) by the laser scanner mentioned above. The polygonal mesh generated and scaled by the standard procedure was then imported into CloudCompare (an open source 3D point cloud processing software) along with the point cloud of front part of the sculpture generated by the laser scanner (Figure 2b). The mesh was then aligned and scaled with reference to the point cloud by using an iterative closest point (ICP) algorithm, which resulted in a scaling of less than 1% of the polygonal mesh, which represents the closeness of sizes after scaling by traditional procedure and scaling by the method described here (Figure 2c).

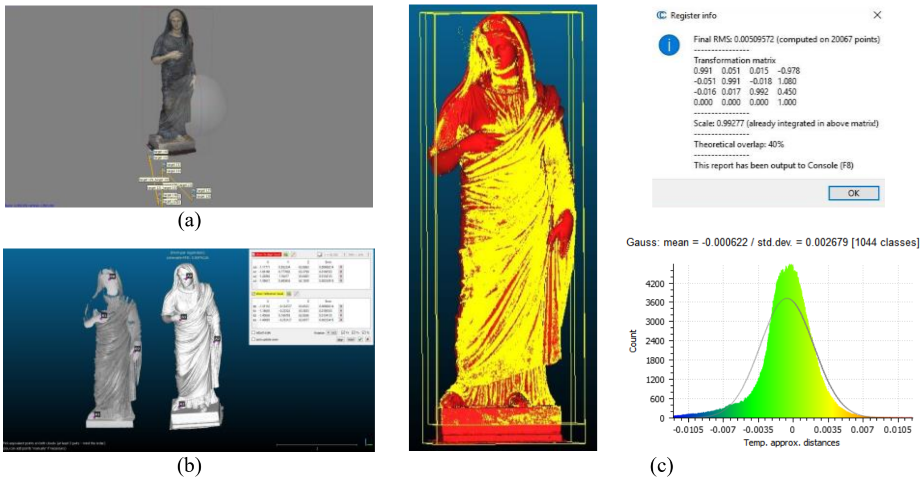

Figure 2. Comparison of different scaling procedures: (a) 3D mesh of a sculpture of Demeter generated and scaled by conventional method in Agisoft Photoscan. The scaling error is 5mm in this case; (b) sculpture of Demeter: imported points cloud from laser scanning (on left) and mesh generated and scaled in Agisoft (on right) (c) mesh aligned and scaled with reference to the point cloud from laser scanner, demonstrating final scaling results and error histogram.

A standard deviation of error of 2.68mm was observed when the distance between the aligned mesh and the points cloud was computed. A part of this error is due to the error associated to the photogrammetric model (i.e. 0.5 mm in this case). Remaining error is directly related to the measurement uncertainty of the laser scanner whose theoretical ranging uncertainty is 2 mm on calibrated targets. In this case the material characteristics of the sculpture (marble) tend to increase this uncertainty [20], [21], making the actual observed standard deviation of error reasonable. However, this local uncertainty does not affect the overall scaling, which is done on the whole shape of the sculpture.

More tests were performed with same procedure on different sculptures of varying sizes and surface qualities: (i) sculpture of Demeter (2m tall with dark rough marble surface); (ii) sculpture of shewolf (1m long with maroon shiny marble surface); bust of Vespasian (0.9 m high with partially shiny white marble surface) and (iii) bust of Domitia (0.8 m high with rough white marble surface). The scaling and alignment errors are compiled in Table 1.

Table 1. Scaling errors and standard deviation of error after distance computation between the scaled models and the points cloud from laser scanner for different sculptures.

	Scaling error %	**Standard deviation mm**
Demeter	0.72	2.68
She Wolf	0.50	4.61
Bust of Vespasian	0.22	3.34
Bust of Domitia	0.18	3.30

It can be noted that the standard deviation of error between the scaled model and points cloud from laser scanner, is solely dependent on the surface quality and measurement uncertainty, as it is highest in the case of the sculpture with most shiny surface (She Wolf) and least in the case of the sculpture with roughest surface (Demeter). On the other hand, the scaling error is maximum for the tallest sculpture and minimum for the smallest sculpture. Hence, it can be concluded that the scaling error is independent of the quality of the laser scan but depends on the whole shape and size of the sculpture.

The scaling of models by the traditional method and the method described here, resulted in almost same output (less than 1% of difference) in all of the examples demonstrated here, therefore this method can be used for scaling photogrammetric models. Even though, this method requires more equipment availability on site, but the data required for the scaling step are represented by a single laser scan image taken at a few meters from the sculpture, which in terms of time takes much less than preparing targets network around the statue and measuring all the relative distances needed for the traditional scaling phase. Therefore, to save time in placing physical targets and measuring their relative position during the photogrammetric survey, we are using the approach of scaling of photogrammetric models with laser scanning.

4.2. Sculptures close to walls

Working in a museum without closing it to the public means adopting the technological choices, as much as possible, according to the situation. The position of the sculpture in the exhibition environment, in many cases, might be very unsuitable for shooting images all around it. This is particularly true for a museum like the Uffizi Gallery, where the number pieces being displayed are enormous, and the space available for exhibition is relatively limited. As a result, many important statues are located close to the walls like the example shown in figure 4a.

In these cases, a possible solution could be to physically move the artifact in the middle of the room to allow a proper photographic shooting all around. But relocating such objects is not an easy task, both for their weight, ranging from hundreds to thousands of kilograms and for their intrinsic value, which makes it mandatory to use the extraordinarily costly and time-consuming processes and precautions.

(a) (b)

Figure 3. (a) HVL-RL1 LED ring light with attachments for different size of lenses; (b) shooting the backside of a sculpture in the museum with ring light attachment.

By analyzing the current situation of the sculptures in the museum located close to the wall, it was found that the 90% were at about 20cm from the wall. Such space allows entering behind the sculpture with a small camera like the one being used in this project, even if with the lens at a very short distance from the sculpted surface. This implies a limited field of view and consequently the need of covering the surface with thousands of images. Also, the zone behind a statue is usually very dark and operating without any additional lighting would have required increasing the ISO setting and opening the diaphragm. But this would have grown the image grain and reduced the depth of field, which is exactly the opposite of what a shooting from a short distance would need.

The solution adopted was to use a wide-angle lens suitable to focus at a very short distance from the surface (18 cm), coupled with a ring illuminator with continuous light and specially designed for video recording (figure 3). This configuration was first tested in the lab on a test object in order to find the optimal balance between light intensity, shooting time and aperture, suitable to capture at that distance with the most limited blurring. By using this combination of wide angle lens and illumination, we were able to capture the back surfaces of the sculptures near to the wall also in very dark areas, which otherwise was not possible.

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(a) (b) (c)

Figure 4. Sculptures close to the walls: a) example of sculpture having only 20 cm between the sculpted surface and the wall; b) model obtained with a 24mm lens, where a huge lacking part is present; c) model obtained with the 12 mm lens and the ring illuminator, completed in all areas close to the wall.

4.3. Camera positioning in high places

Carrying out a photogrammetric project on large artifacts, like those owned by Uffizi gallery (up to 3m high), requires the movement of the camera all around the object and therefore also in positions not easy to reach. Two different approaches are usually used to reach higher places for a photogrammetric survey: climbing up the scaffoldings all around the artifact to be digitized or using a drone.

The first approach, generally used for restorations of the statues, involves a lot of additional work for mounting the structure of the scaffolding and for moving it around the object resulting in a solution too slow and costly especially for a systematic digitization process involving so many pieces. The drone was instead problematic regarding the related flight authorizations. The strict regulations about unmanned flying vehicles in the Italian art cities, where the areas hosting the sculptures are visited by hundreds of tourists every day, prevents the authorities to allow any flight unless the area is closed to the public. And this condition was not practical to be reached unless a huge amount of time would have been spent in dealing with the associated bureaucratic issues. Therefore, for the IU-Uffizi project, none of the two approaches were followed.

Therefore, the simplest solution was to use a tall monopod on top of which the camera was mounted. The camera used for this purpose, has a feature to be remotely controlled with a portable device like a smartphone or a tablet. Both the viewfinder and all the photographic controls can be transferred to a handheld device, and an operator can remotely decide to expose, focus and shoot. This specific monopod is 8m aluminum pole made by 4 sections of 2m each, which can be used modularly for reaching 2, 4, 6 or 8m of height (Figure 5). It was remarkably suitable for the gigantic sculptures in the "Loggia dei Lanzi," in front of the Uffizi gallery and for a part of the Uffizi collection. Such statues are from 2 to 3 meters high, and lie on a 1.5 to 2m basement, reaching easily 4 to 5 meters of absolute height from the floor. Imaging these artifacts from 8 m allows to capture all the details of the top surfaces that would be otherwise lost. In addition, reducing the height at steps of 2m allows to capture images all around the sculpture from different heights. Even though this method requires extra personnel, at least one person for holding the pole and one for capturing images remotely, but the overall time of survey is much more less than using other methods.

Figure 5. Monopod for shooting of tall sculptures with four section structure.

5. Conclusions

An ongoing massive digitization project has been explained in terms of the methodologies and technical choices adopted to digitize maximum number of museum artifacts in minimum time and to create models containing maximum information in terms of geometry and surface characteristics. The project has already produced more than 300 models of the most complex sculptures till now. The website of this project (www.digitalscupture-uffizi.org) offers interactive 3D models, published using the web service Sketchfab, embedded on a page which also includes the traditional information typically provided for a work of art (name, artist, date, material, dimensions, principal restorations, bibliography) as well as technical metadata about the author of the model, the method of 3D data capture, and the software used for 3D modeling ad 3D editing. It is anticipated that at the end of each academic year, the database will be updated to include the newly modeled sculptures. When it will be launched, this year, the preliminary website should present ca. 300 sculptures.

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