

3D Virtual Reconstruction and Augmented Reality Visualization of Damaged Stone Sculptures

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Abstract. This paper proposes the integration of photogrammetric reconstruction, 3D modelling and augmented reality application in order to achieve the complete visualization of a stone sculpture even if highly damaged or fragmentary. The first part of the research aims to the reconstruction of the original appearance of an incomplete sculpture, by using photogrammetric techniques based on standard resolution photos and, if possible, free software in order to obtain a digital model; then, we integrate this model with other 3D digital data (from other sculptures of the same period) or by 3D modelling in accordance with art-historical and archaeological studies. The second part of the research consists of embedding the 3D model in a custom Android application able to render in real-time the reconstructed parts of the damaged sculpture. Then, the rendering is overlaid on the video stream of the real scene and, as a result, a complete 3D digital model of the sculpture is achieved and could be visualized through a Virtual Reality viewer. As a case study, we focus on a Roman stone funerary sculpture of a male lion conserved in the Museo Lapidario Estense of Modena (Italy), which lacks of its muzzle and its four legs. The original appearance of the lion may be supposed by modelling and integrating the damaged sculpture with other photogrammetric details of funerary lion sculptures of the same period, according to art-historical sources. Finally, the lion is visualized through an augmented reality application which digitally overlays the reconstructed parts on the real sculpture.

Keywords. Photogrammetry, Augmented Reality, Virtual modelling, Real-time visualization, Cultural heritage.

1. Introduction

The role of digital technology in the cultural heritage field ranges from reconstructing to monitoring, from measuring to digitizing and visualization. Monitoring and investigating ancient structures or sculptures lead to use 3D models in a diagnostic perspective in order to study structures along with their actual dimensions, their stability, their modifications over time, etc. [1]. In measurement technology, data that were once extremely difficult and possibly dangerous to collect can now be collected and processed using only a digital camera and off-the-shelf software. Currently, digital close-range photogrammetry has made it possible to efficiently model a variety of structures in a budget-friendly manner [2]. Other photogrammetric applications deal with the reconstruction of digital models by means of images collected on the web [3,4], as in the case of strongly damaged or destroyed artefacts in order to reconstruct their appearance as they were before.



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In [5], digital technologies are tested to assist stone carvers in restoring carved elements while also learning from the sculptors and masons to better understand their approach when conserving or restoring a sculptural element.

For most of these aims, the photogrammetric techniques have increased their central role in recent years, thanks to the support of better hardware and software, even open-source or free one, as tested by [6]. They focus on the accuracy and the metric content of the final result, which is globally positive even when low textured or reflective surfaces are present in the 3D scene.

Some technologies are used to reconstruct and show the complexity of the territory and its heritage, including 3D scanning, 3D printing and Augmented Reality (AR) [7]. Some museums and archaeological sites already exploit the potential of digital tools to preserve and spread their heritage but interactive services involving tourists in an immersive and more modern experience are still rare.

Modelling of complex figures using photogrammetric software is being increasingly used in the field of cultural heritage as an alternative to techniques based on 3D scans, due to its low cost and flexibility of use [8]: these authors applied this technique to the modelling of Mesoamerican sculpture, namely chacmool of Tenochtitlan, for obtaining a precise three-dimensional model, i.e. a complete record of its current state, used for the preparation of interactive museum models and for the production of stereoscopic videos.

The present paper focuses on the potentiality of integrating photogrammetry, for 3D reconstruction, with the AR benefits, in order to increase the interaction with the artefact.

As a case study, we focus on a Roman stone sculpture of a male lion conserved in the Museo Lapidario Estense (Estense Lapidary Museum) of Modena (Italy), which lacks of its muzzle, its four legs, and the end of its tail. The original appearance of the lion may be supposed by integrating the damaged sculpture with parts achieved by photogrammetric reconstruction of other sculptures of the same period and conveniently modified and re-modelled. Finally, the lion is visualized through an AR application which digitally overlays the reconstructed parts on the real sculpture.

The paper is structured as follows. Section 2 describes the general method, Section 3 presents the method application to a case study, which is a damaged Roman sculpture of a funerary lion, and finally Section 4 draws some final remarks.

2. Method

The first part of the research aims to the reconstruction of a damaged sculpture, by using photogrammetric techniques based on standard resolution photos and, if possible, on free software in order to obtain a first model; then, in order to integrate the missing parts of this model, we identify and digitally reconstruct other 3D sculptures (i.e. other sculptures of the same period) by photogrammetry, and by 3D modelling in accordance with archaeological studies and hypothesis from art-historians, aiming to achieve the original appearance of the damaged sculpture.

The steps are listed below:

- Photogrammetric reconstruction of the damaged sculpture and of the other sculptures that may provide some of the missing parts.
- Integration of these parts into the main model, if necessary by partially re-modelling them in order to reconstruct missing details.
- Finally the real model is “augmented” by the additional parts: in order to improve the interaction with the observer, a dedicated AR application is developed.

3. Case study

The statue selected as a case study depicts a male lion and is located inside the Museo Lapidario Estense (Estense Lapidary Museum of Modena), in the west span E, with number 52. It can be historically placed in the first half of the 1st century CE. In [9,10], the authors hypothesize that this lion could be part of a decorative element belonging to an ancient Roman funerary monument. The statue is realized in Vicentina stone, which was extracted from the Berici Hills (Vicenza, Italy) and sent to Modena by fluvial way, and often employed in the artistic field.

The lion statue (Fig. 1) appears, although damaged, in excellent condition: the lion is represented in frontal position, shows the muzzle slightly turned to the left side, compared to the observer. The lion is installed on a base whose dimensions are 620 x 1400 x (height) 345 mm. The locks of the lion mane are clearly visible and well maintained, extending over the entire front and back of the statue. On the sides it is possible to glimpse its muscular bundles and the ribs, and in the back part, starting from the right to the left it is possible to observe its tail, which lacks of its end, that embraces most of the lumbar area, while the muzzle and the four legs are missing. As regards the position of the legs, the hind ones may be thought to be similarly folded as if the lion was sitting, while the front ones appear to differ from each other, the left one (with respect to a frontal observer) seems to have a slightly inclined direction compared to the base, as the ribs still present may suggest that the lion was not with the legs perfectly perpendicular to the floor. As far as the other front leg is concerned, it is assumed that it was raised and taken forward, as if the lion was grabbing a prey or tending to someone or something.

Sculptures of this kind were widely used in Roman funerary structures of the Augustean era, similar elements are linked to other monuments such as the contemporary ones of Aquileia (Udine, Italy) and Sepino (Campobasso, Italy). The statue of this lion should have three other similar sculptures, placed in guardianship of a monumental sepulcher that had to rise along the ancient consular road “via Aemilia”. Monuments of this type and size had to be very common in Modena, as in the case of the two Roman lions on the sides of the main door of the Cathedral (Duomo) of Modena (see next sub-section).



Figure 1. The funerary lion statue (first half of the 1st century CE, Museo Lapidario Estense, Modena, Italy).
Photo credit: Marianna Grandi.

3.1. Photogrammetry of the damaged lion and the other sculptures

The first part of the research aims to the reconstruction of the original appearance of the incomplete sculpture of a funerary male lion, by using photogrammetric techniques based on standard resolution photos and, if possible, free software in order to obtain a 3D model. A first photogrammetry reconstruction is performed within the free version of software ReCap (Autodesk) by means of 95 photos (Standard compact camera Nikon P310, 16.1MP CMOS Sensor, Sensor size: 1/2.3" (~ 6.16 x 4.62 mm), Max. image resolution: 4608 x 3456), some of them are shown in Fig. 2. However, in this free version 100 is the maximum number of photos that can be processed so, because some details are missing in the

achieved model, we further reconstruct the 3D model within the professional software PhotoScan (Agisoft) by means of 130 photos, which generates a more detailed textured model of the lion (Fig. 3), in particular in its back and bottom side.



Figure 2. Examples of the photographic images used as inputs for the photogrammetric reconstruction.



Figure 3. Digital model reconstruction: (left) the model as output from the software PhotoScan (Agisoft) and (right) after removing the background scene.

Similarly, we reconstruct: 1) the right one of the two Roman lions of the main door of the Cathedral of Modena (Fig. 4a), which are considered of the same age and originally with the same function (i.e. funerary lions), but re-used as building materials during the Cathedral of Modena construction [11,12]; 2) a crouching funerary lion of the 2nd Century CE (Fig. 4b), kept in the Capitoline Museum of Rome (Italy) [13], in order to extract some details.

3.2. Details integration, modelling and texturing.

The comparison between the damaged lion and the other two sculptures may suggest two different positions of the lion body: the lion may 1) have a crouching position or 2) stand on its four legs. Two different digital models of the funerary lion are then reconstructed in order to validate its integration with the parts achieved from the other models. For the crouching position, we extract the muzzle (Fig.

4c) from the Cathedral lion, according to [11, 12], while the front and hind legs (Fig. 4d e 4e) and the tail end (Fig. 4f) are achieved from the crouching funerary lion of the Capitoline Museum. For the standing position, we extract the muzzle (Fig. 4c) and the hind legs (conveniently remodeled as in Fig. 4g), while the front legs (with the standing one conveniently remodeled as in Fig. 4h) and the tail end (Fig. 4f). Then, we integrate these parts with the damaged lion sculpture model, by modifying the texture and by partially re-modelling them within the software Meshmixer (Autodesk). The additional parts need to be scaled, cut, refined, and smoothed: the two final 3D models are shown in Fig. 5 and will be used for the next phase of AR implementation.

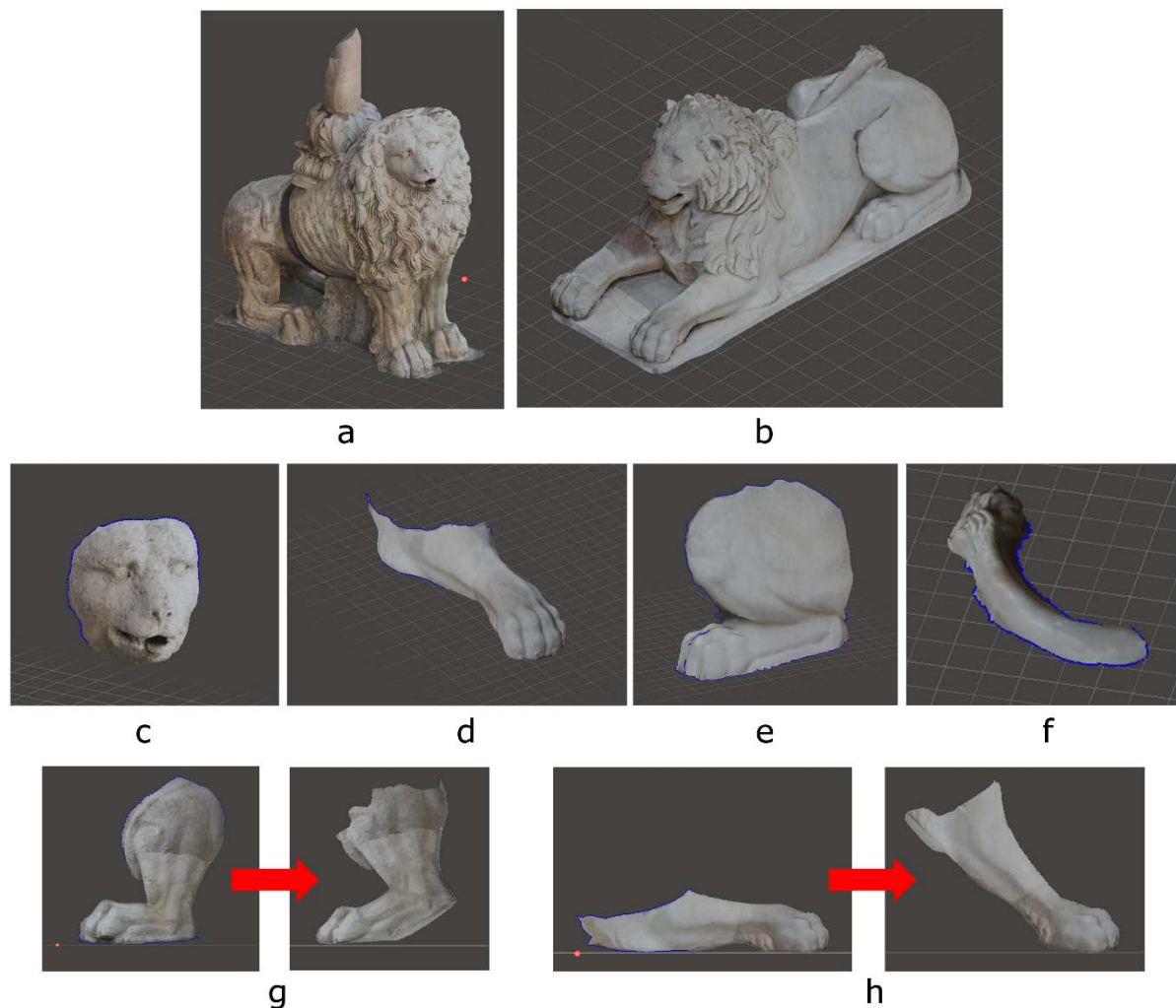


Figure 4. Top: The lion of the Cathedral of Modena (a) and the lion of the Capitoline Museum of Rome (b). Middle: Details from the other lion sculptures: muzzle (c), front leg (d), hind leg (e), tail end (f). Bottom: Re-modelling of the hind leg of the Cathedral lion (g) and the front leg of Capitoline lion (h).



Figure 5. 3D models of the lion in the two positions: Left: Crouching; Right: Standing on the four legs.

3.3. Implementation of AR

The AR application is implemented within the Unity engine platform (Unity Technologies) by means of EasyAR tracking technology library. Its implementation requires the following steps:

1. The EasyAR plugin package is imported into the Unity platform.
 2. The scene needs to be set up, whose essential components are already available (as prefab) in the plugin package. In the EasyAR, the following tools are available: a logical abstraction allows interfacing with the hardware device camera (CameraDevice Behaviour); a virtual camera of the scene allows the overlap between video flow and real-time 3D rendering (ARCamera Behavior); a tool for target tracking (Tracking ImageTracker); a component that detects and traces the ImageTarget (ImageTracker); a flat image that can be traced by an ImageTracker (ImageTarget).
 3. The image to be traced required to be set: Once a new ImageTarget is inserted in the scene, the image (in .jpg or .png format) is copied in the subfolder of the "StreamingAsset" project, then set the X and Y proportions in the size of the ImageTarget in a manner consistent with those of the reference image. Assign an ImageTracker present in the scene in the Loader field. Then, at this point the application may recognize and trace the image.
 4. The object to render is assigned to the tracker of the images: the object to visualize is set as a "child" of the ImageTracker. Specifically to the lion sculpture, which is a voluminous artefact, the parallelepiped base of the statue is considered as a reference marker, and an ImageTarget is generated for each face of the base. Each ImageTarget is positioned in such a way as to coincide with its reference face in the 3D model of the statue.
 5. At this point we obtain a system of 3 ImageTargets (ignoring the upper and the back side of the statue). The reconstructed parts of the lion (Fig. 6) are then added as a child within each of the 3 ImageTargets. Then, we can trace the base and see the reconstructed parts which will be overlaid on the lion sculpture: nevertheless, only one ImageTarget at a time is required to be traced, in order to avoid disturbances and overlaps, by managing the priority based on the last ImageTarget detected. To this aim, a further part of the code is implemented, in order to let the observer turning around the lion for about 180° without losing tracking.
 6. In order to use the AR application with the VR viewer, the adaptation for stereographic rendering requires that the display will be split in two parts: one will render for the left eye (left camera), the other one for right the eye (right camera). This is achieved by inserting in the scene two virtual cameras spaced apart by 0.6 on the horizontal axis and assigning to each a specific area on which to render in the viewport respectively $x = 0$, $y = 0$, $w = 0.5$, $h = 1$ for the right camera and $x = 0.5$, $y = 0$, $w = 0.5$, $h = 1$ for the left camera. This requires a double rendering pipeline: the scene is rendered twice. This could be a critical factor in the case of highly complex scenes, but negligible in the present case study.
- The AR application is able to render in real-time the reconstructed parts of the damaged sculpture by overlaying them on the video-stream of the real scene (Fig. 7) and, as a result, the complete 3D digital model of the sculpture is achieved and could be visualized through a VR viewer.

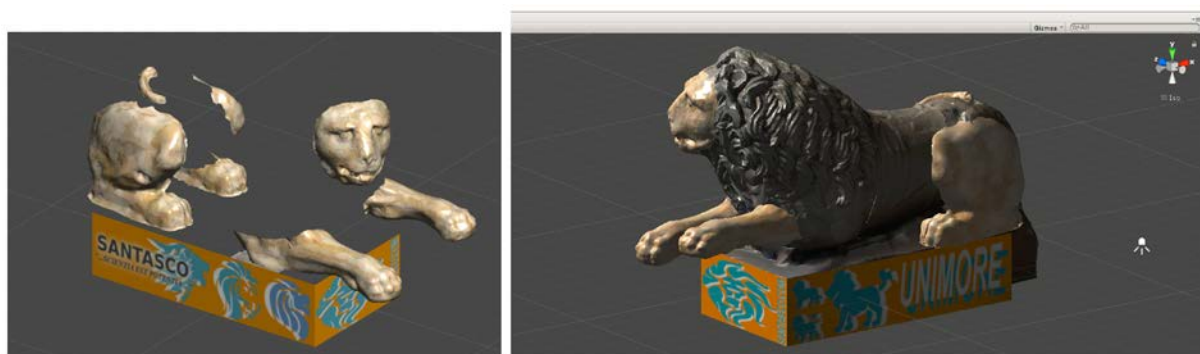


Figure 6. Tracking of the images (as reference markers) on the sculpture base for the visualization of the reconstructed parts (left) and their overlaying on the lion model (right).



Figure 7. Augmented Reality scene of the lion in crouching position.

4. Discussion and conclusion

This paper proposed a method for reconstructing and integrating the missing parts of stone sculptures by means of photogrammetric and AR techniques. The damaged sculpture is first digitally reconstructed and integrated with the missing parts, and then “augmented” by means of the digital models extracted and remodelled from other sculptures.

The method requires to reconstruct different models, which need to be compatible with the damaged one, in terms of surface finishing of the stone, colour, texture, or however, it requires to work extensively the parts and their feature. The selection of the “missing parts” requires the study and the investigation of models with similar characteristics, according to art-historical and archaeological studies. Due to photogrammetry, the lighting conditions may be a critical point in the method, which requires to post process the images in order to achieve better results. The use of a VR viewer requires a double rendering pipeline, so that the scene needs to be rendered twice: this could be a critical factor in the case of highly complex scenes, so the virtual model may require to be decimated and simplified.

On the other hand, the method is able to generate a tool for the assessment of hypothetical reconstruction of damaged sculptures, supporting the observer with AR visualization. As a further development, we will integrate the reconstructed lion within the scene of the whole funerary monuments, by means of AR.

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Photo credits

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References

- [1] Capra A, Bertacchini E, Castagnetti C, Rivola R, Dubbini, M 2015 Recent approaches in geodesy and geomatics for structures monitoring *Rendiconti Lincei* 26(1) 53-61
- [2] Leitch K R, M B Coon 2012 Noncontact Modeling of Structures Using Close-Range Digital

- Photogrammetry *Practice Periodical On Structural Design And Construction*.
- [3] Vincent M L, Flores Gutierrez M, Coughenour C, Lopez-Menchero Bendicho V.M., Remondino F, Fritsch D. 2015 Crowd-Sourcing the 3D digital reconstructions of lost cultural heritage. In: 2015 Digital Heritage, 1 pp 171–172
 - [4] Gherardini F, Leali F 2016 A Framework for 3D Pattern Analysis and Reconstruction of Persian Architectural Elements *Nexus Network J.* 18(1): 133–167
 - [5] Ouimet C, Gregga J, Kretz S, Chandler Ca, Hayes J 2015 Documentation and dissemination of the sculptural elements of Canada's parliamentary buildings: methodology development and evolution, a case study. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XL-5/W7, 2015
 - [6] Toschi I, Rivola R, Bertacchini E, Castagnetti C, Dubbini M, Capra A (2013) Validation tests of open-source procedures for digital camera calibration and 3D image-based modelling *ISPRS Archives – Volume XL-5/W2*, p. 647-652.
 - [7] Castagnetti C, Giannini M, Rivola R 2017 Image-based virtual tours and 3d modeling of past and current ages for the enhancement of archaeological parks: The visualversilia 3d project *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XLII- 5/W1 pp 639-645
 - [8] Modeling of an aztec sculpture with photogrammetry. Geneviève LUCET, Araceli CASAS. Facultad de Arquitectura, Universidad Nacional Autónoma de México. Ciudad Universitaria, Méx. D.F., Mexico 25th International CIPA Symposium 2015, 31 August – 04 September 2015, Taipei, Taiwan Another reference.
 - [9] Malmusi C 1930 Museo Lapidario Modenese (Modena, Franco Cosimo Panini)
 - [10] Giordani N, Paolozzi Strozzi G 2005 Il Museo Lapidario Estense, Catalogo generale
 - [11] Rebecchi F 1984 Il reimpiego di materilae antico nel Duomo di Modena Lanfranco e Wiligelmo. Il Duomo di Modena.
 - [12] Sandonnini T Cronaca dei restauri del Duomo di Modena (1897-1925) Aedes Muratoriana (Modena, Italy).
 - [13] <http://capitolini.info/scu00050/?lang=en> (accessed March 15, 2018).