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ENHANCING HERITAGE FRUITION THROUGH 3D VIRTUAL MODELS AND AUGMENTED REALITY: AN APPLICATION TO ROMAN ARTEFACTS

MEJORA DE LA DIFUSIÓN DE CONTENIDOS CULTURALES DEL PATRIMONIO MEDIANTE MODELOS VIRTUALES 3D Y REALIDAD AUMENTADA: UNA APLICACIÓN A LOS ARTEFACTOS ROMANOS

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Highlights:

- Digital practice is not understood as a prerogative of a small number of people, but as a tool to guarantee and expand artefact fruition, using standard devices and free and open source software.
- Experimentation of new settings to re-contextualize artefacts and establish possible links among them, offering engaging and customized experiences to improve their accessibility and enjoyment.
- Promotion of artefact fruition not only in but also outside museums, such as in a classroom or an open and shared space, opening to new approaches in the fruition of cultural heritage.

Abstract:

The spatial characteristics of museum exhibitions may limit visitors' experience of the artefacts on display. In the case of large artefacts, limited space may affect their whole visualization, or inhibit the visualization of the details farthest from the observer. In other cases, the storage of artefacts in distant sites (museums or archaeological areas) may influence their knowledge process or the possibility for comparative analysis. Moreover, the precarious state of preservation of some artefacts, with damaged or missing parts, makes it difficult to perceive their original appearance. To overcome these limitations, we propose an integrated approach based on 3D virtual models and Augmented Reality (AR) to enhance the fruition of artefacts, improving their visualization, analysis and personal/shared knowledge, also by overcoming space and time constraints. The final AR application is an easily accessible tool for most users from a mobile device, used both inside and outside museums, opening new perspectives for fruition. The framework encourages the use of free and open source software and standard devices, to maximize their dissemination and exploit the potential of such technologies, which is far greater than current use in the cultural heritage field. Selected case studies to test and validate the integrated framework are proposed, dealing with some Roman artefacts found in the area of Modena (Italy). The first is a Roman floor mosaic, found in *Savignano sul Panaro* (near Modena) in 2011, of which less than half of its original 4.5 x 6.9 m surface is preserved. The others are two Roman funerary lion sculptures: the first is one of two lions flanking the main door of Modena Cathedral, and the second, well-preserved but damaged, is housed in the Museo Lapidario Estense of Modena. Finally, the application was tested by museum experts and visitors both inside and outside the museum, and positively assessed.

Keywords: virtual modelling; image-based reconstruction; augmented reality (AR); real-time visualization; virtual museum; Roman archaeological objects

Resumen:

Las características espaciales de la exhibición en museos puede limitar en los visitantes la experiencia de los artefactosque se presentan. En el caso de artefactos de gran tamaño, la limitación de espacio puede afectar su visualización completa o inhibir la visualización de los detalles más lejanos al observador. En otros casos, el almacenamiento de artefactos en sitios lejanos y apartados (museos o zonas arqueológicas) puede influir en su proceso de conocimiento o en su análisis comparativo. Es más, el precario estado de conservación de algunos artefactos, con partes dañadas o perdidas, hace difícil percibir su aspecto original. Para superar estas limitaciones, proponemos un enfoque integrado de modelos 3D y realidad aumentada (RA) que mejore el disfrute de los artefactos, mejorando su visualización, análisis y conocimiento personal/compartido, incluso sobrepasando las limitaciones de espacio y tiempo. La aplicación final es una herramienta fácilmente accesible para la mayoría de usuarios mediante un portátil, que se use dentro, pero también fuera de los museos, abriendo nuevas perspectivas de disfrute. El enfoque promueve el uso de software libre y gratuito y herramientas estándar, con vistas a maximizar su amplia distribución y reivindicar las potencialidades de dichas tecnologías, que son superiores a su actual uso en el campo del patrimonio cultural. Se proponen casos de estudio seleccionados para testear y validar el enfoque integrado, a partir de algunos artefactos

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Romanos encontrados en la zona de Módena (Italia). El primero es un suelo de mosaico Romano, encontrado en Savignano sul Panaro (cerca de Módena) en 2011, que conserva menos de la mitad de sus 4.5 x 6.9 m de superficie originales. Los otros son dos esculturas funerarias romanas de león: el primero es uno de los dos leones que flanquean la puerta principal de la Catedral de Módena, y el segundo, bien conservado pero dañado, se almacena en el Museo Lapidario Estense de Módena. Finalmente, la aplicación se prueba por expertos del museo y visitantes dentro y fuera del museo, y se evalúa positivamente.

Palabras clave: modelado virtual; reconstrucción basada en imágenes; realidad aumentada (RA); visualización en tiempo real; museo virtual; objetos arqueológicos romanos

1. Introduction

The spatial characteristics of museums and exhibitions are crucial for the process of knowledge and experience offered to visitors (Vergo, 1989; Psarra, 2005; Rees Lehay, 2005; Screven, 1986; Shackley, 1999; Brawne, 1965, p. 8-10; and more recently, Krukar, 2014; Tucci, Cini, & Nobile, 2011), in terms of visitors' perception, capability of storing images and information, comparative analyses, etc. Moreover, due to space limitations, artefacts may be stored in different sites (museums or archaeological areas) or excluded from physical museum itineraries, making them inaccessible.

The use of digital approaches in managing cultural heritage may overcome these issues, and furthermore enhance the fruition of artefacts through new ways of communicating and interacting with visitors (Guidi, Trocchianesi, Pils, Morlando, & Seassaro, 2010), leading to virtual museums. According to Tsichritzis and Gibbs (1991), Skolnick (2005), Charitos, Lepouras, Vassilakis, Katifori, & Halatsi (2000) and Caspani, Brumana, Oreni, & Previtali (2017), they can be defined as additional ways of disseminating contents and providing knowledge about cultural heritage, emerging from the ongoing process of crossbreeding between museums and digital technologies.

In the articulated and multidisciplinary definition of virtual museum concepts, which is still undergoing investigation (V-MUST; Polycarpou, 2018; ICOM), technologies contribute with different aims and scopes, supporting but not replacing traditional museum practices, and indeed further enhancing them. An artefact can be processed through numerous digital technologies, from simple digital photographs to 3D virtual models or virtual environments, even more quickly and with ever greater resolutions and detail capabilities. Thanks to digital technologies, the real artefact may be flanked by digital models, information, images and documents found during research, and these can be manipulated, analysed and made accessible to people located both on-site and remotely (i.e. in places other than the museum itself) (Luigini, Brusaporci, Vattano, & Tata, 2019).

Therefore, digital technologies can open up the possibility of wide-scale virtual access, with two main effects:

- Enhancement of the role of visitors, from simple viewer to active subject (Black, 2005; Guidi et al., 2010).
- Enhancement of the territory, promoting its knowledge and its safeguarding processes (Caspani et al., 2017; Luigini et al., 2019; Maícas & Viñals, 2017).

Among those digital technologies, literature presents an extended use of 3D digitization tools for capturing real artefacts, objects, documentation and scenes, without their direct modelling. Together with 3D scanning, range-based or image-based techniques provide virtual models of real artefacts without contact (Guidi and Remondino, 2012). The morphological model may be integrated with a texture that reproduces the surface appearance of the real artefact, such as its finish or colour. The final 3D model provides the end-user (e.g. visitor, scholar, researcher, etc.) with a permanent source of knowledge, analysis, exploration of details, which:

- Is a true (digital) copy of the real artefact;
- Does not need to be physically in the museum;
- Supports the comparison of a plurality of findings and sources located in different places;
- In addition to distance, sometimes it can also eliminate time, allowing users to analyse artefacts that no longer exist or are seriously compromised by damage, atmospheric phenomena, natural disasters, etc.

Furthermore, these 3D models may support user interactions in many other ways:

- 3D modelling techniques and tools can be used to digitally restore an artefact to its original form or colour, evaluating hypotheses and comparing models (e.g. Scopigno, Corsini, Callieri, & Dellepiane, 2011; Rojas-Sola & de la Morena-de la Fuente, 2018; Fazio, Lo Brutto, & Dardanelli, 2019; Gherardini, Santachiara, & Leali, 2018).
- Production of archaeological documentation with a three-dimensional approach, tested on the archaeological site (e.g. Santos, Ritz, Fuhrmann, & Fellner, 2017; Valente et al., 2017).
- 3D documentation for conservation purposes (e.g. Tucci, Bonora, Conti, & Fiorini, 2017; Bici, Guachi, Colacicchi, D'Ercoli, & Campana, 2019; Lo Brutto, Garraffa, Pellegrino, & Di Natale, 2015; Ouimet, Gregga, Kretz, Chandler, & Hayes, 2015).
- 3D models, also developed by range-based or image-based reconstruction, are used for creating replicas (e.g. Wilson et al., 2018; Volpe, Furferi, Governi, & Tennirelli, 2014).
- Models can support the development of a virtual and interactive exhibition environment (e.g. Tucci et al., 2011).

Many researchers focus on developing tools and techniques to enhance efficiency and reduce model computational weight without losing any detail resolution, using standard devices or perhaps free and open access software (Parras, Cavas-Martínez, Nieto, Cañavate, & Fernández-Pacheco, 2018).

While digital 3D reconstruction techniques increase the fruition of artefacts, guaranteeing accessibility without space and time constraints, this is even truer when using interactive digital environments that allow visitors to participate and manipulate real or digital artefacts, in real or digital scenes. Among them, Augmented Reality (AR) technology allows users to join an immersive experience, integrating real and digital objects, interacting with the artefacts in a more spontaneous way as in the case of a viewer, to experience the artefacts in their real dimensions. Similarly, but with an opposite approach, AR may also allow the integration of real artefacts into digital environments, for example by reconstructing the first site of origin, and thus contextualizing the artefacts in their original context (Noh, Shahrizal, & Pan, 2009; Castagnetti, Giannini, & Rivola, 2017; Younes et al., 2017; Purnomo, Santosa, Hartanto, Pratisto, & Purbayu, 2018). Again, the integration of AR with 3D capturing and 3D modelling offers the possibility of proposing a hypothesis of restoration and its virtual reconstruction, providing the user with a scientific simulacrum of the original artefact (Antinucci, 2014). In other applications, AR allows the overlapping of the history of the artefact, which the museum intends to communicate, or the particular role of the artefacts themselves in the exhibition layout. Therefore, it grants the possibility of developing new spatial parallelisms, offering a new and stimulating hybrid dimension (Ludovico, 2012).

On one hand, AR combined with the functionality of georeferencing users in space (if connected to a ground coordinate system) offers contents within closed spaces, even in larger museological contexts, by implementing indoor navigation systems. On the other hand, the synergic use of these technologies also makes it possible to take the artefact "out" of the museum, so that it can be visualized in a classroom, a square, in both outdoor and indoor places, leading to a new approach in virtual museums (Sylaiou, Liarokapis, Kotsakis, & Petros, 2009). The artefact may become the centre of education and information activities that are generally not applicable in the context of the traditional museums.

AR technologies benefit from continuous improvements in hardware and software, allowing more complex models integrated into the real world to be managed, possibly even without requiring markers and using standard devices such as smartphones, tablets or viewers. However, AR digital models must guarantee the excellent resolution of the artefact (in terms of dimensional accuracy and surface texture), high levels of detail, but also reduced computational weight in order to be easily manipulated by the AR application. For this purpose, 3D digital models require pre- and post-processing phases, focusing on higher image quality and point cloud decimation.

This article presents the integration of 3D capturing technologies and AR carried out on Roman artefacts located in and near the city of Modena (Italy). The fragmentary nature of the artefacts, the great distances between the museums and archaeological sites in the territory, and the potentially unfavourable spatial characteristics of museums and exhibitions make it difficult to appreciate, analyse, study and compare artefacts. We, therefore, propose a framework for integrating technologies and tools for 3D capturing and AR to improve user experience with regard to artefact fruition. A fundamental phase is the development of a library of 3D models, images, references and information to be integrated into the AR environment. The AR environment will, therefore, act as a link for different sources and types of knowledge (e.g. archaeology, art history, materials and restoration aspects).

The proposed approach is applied and assessed on selected case studies related to Roman artefacts. The first case study concerns the floor mosaic of a Roman villa, found in the province of Modena that, after having been removed from the original site, was initially housed in the *Musei Civici* (Civic Museums) of Modena and then definitively placed in a small, specific building near the site of origin. Many sources dealing with this –only partially preserved– mosaic are available, so the 3D model can be enriched with information and constructive hypotheses. The second case study concerns the statues of funerary lions, which were found in the current urban area of Modena, some of which are only partially preserved. These sculptures are now out of their original context, exhibited in museums, while in the past some were used as construction materials in other monuments, distorting their original function. Therefore, we developed 3D digital models of these artefacts and integrated them in AR environments with a view to promoting their understanding and fruition.

The paper is organized as follows. In section 2, we introduce the approach and tools developed. Section 3 reports on the application of the approach to the selected case studies. In Section 4, we discuss the implementation of the approach, and finally, draw the conclusions.

2. Methods and tools

The approach proposed in this paper is based on the integration of two steps: firstly, the 3D digital reconstruction of real artefacts, and secondly, its integration within an AR application, in order to "augment" the real world with digital artefacts and annotations.

First of all, we use 3D capturing techniques to generate reality-based 3D models based on passive sensors and image data (image-based approach). For this purpose, we use close-range photogrammetry based on standard resolution photos and, where possible, free software. The pre-processing phase requires the assessment of image quality, the balanced distribution of images around the subject, the light conditions and the presence of shiny areas or bright reflections on the surface of the artefact. The post-processing phase involves cutting the whole scene surrounding the artefact and, moreover, decimating the point clouds without affecting the resolution of the 3D model. In this work, we perform the 3D reconstruction by means of the free and open source software Meshroom, based on the AliceVision Photogrammetric Computer Vision framework (Meshroom by GitHub).

Depending on the state of preservation of the artefacts and the aims of the AR strategy, an intermediate phase may be required. This may be the case when dealing with damaged or missing parts of the artefact or when having to speculate on the real appearance of the artefact. In these cases, an additional 3D model may complete the missing parts or areas on the basis of the adjacent ones by 3D direct modelling or using additional sources, according to archaeological studies and hypotheses made by art historians. In the case of 2D artefacts, a high-resolution image before damage (if available) may serve the same purpose.

The second phase deals with AR, a technology that augments the user's current experience in the real world by adding digital data to it (Linowes & Babilinski, 2017). Therefore, an AR application aims to augment or annotate the user's reality by overlaying a view of the real world with computer graphics (Lanham, 2018). The resulting image is the superposition of a virtual object into the user's reality, and the screenshot is rendered real-time on a mobile device or viewer.

In recent years, the most commonly used method in AR applications is marker-based tracking, which has many limitations in complex or outdoor settings (i.e. the usage of markers is restricted on site). However, new markerless methods based on natural feature tracking are available, and other innovative methods are constantly being developed. An analysis of recent libraries and plug-ins for markerless AR applications is presented in (Blanco-Pons, Carrión-Ruiz, & Lerma, 2019), considering factors such as distance, occlusion and lighting conditions that affect user experience in both indoor and outdoor environments, with the purpose of supporting the application developer in selecting the best library and plug-ins based on user preferences.

Accordingly, in our approach, we use a Unity3D version (i.e. Unity 2017.2.0f3 – 64 bit) suitable for both Windows 10 and macOS operating systems. Unity3D has several options for creating AR applications, available as plug-ins. Among these, we select ARCore[1], a Google platform for building AR applications, working with native to Android devices using the Java programming language, based on natural feature tracking.

ARCore uses three key technologies to integrate virtual content with the world through the camera: motion tracking, environmental understanding and light estimation (Glover, 2018):

- It tracks the position of the device (e.g. a mobile phone or tablet) as it moves within the real world;
- It understands the environment by detecting the size and location of all types of surfaces: horizontal, vertical and angled surfaces, e.g. the ground (Fig. 1);
- It estimates the current environmental lighting conditions.

Therefore, ARCore identifies interesting points (called features) from the device camera sensors, and is able to determine both the position and the orientation of the device as it moves. Then, it builds its own understanding of the world around it. In particular, ARCore interpretation of the real world lets the user place objects, annotations or other information in a way that integrates them seamlessly with the real world.

Thanks to visual enhancements, further details such as lighting and shadows of the AR object are added to the scene by superposition into the real environment. Thanks to motion tracking, the user can move around and view objects from any angle. In particular, we highlight one of the aims of the developer (i.e. Google), which suggests one possible application as that of "annotating a painting with biographical information about the artist" (ARCore).

We should underline that, for the purpose of this paper, the AR application is required to augment the real scene also by replicating the 3D digital model of the real artefact, which is then further integrated by annotations, objects, texts, etc. in order to digitally take the artefact outside the museum. However, different approaches may be developed based on the same integration of techniques. For example, if the AR application is required to run inside the museum building, the AR may simply augment the real artefact by overlaying annotations or other 3D models for comparison, without needing to visualize its digital clone.

(a)

(b)

Figure 1: Detection of the size and location of the floor planar surface: a) outdoor, and b) indoor floor.

3. Results

The context of the application of this research paper is the city of Modena, in Emilia-Romagna (Italy), and the surrounding areas. The city of Modena dates back to the Etruscan period, when it was named "*Muthuna*", but was first invaded by Gauls in the 4th century B.C. and, subsequently, two centuries later became a Roman military castrum under the name of Mutina (Kleinhenz, 2004, pp. 724-725; Fields, 2018, pp. 87-88). The key date in the history of Modena (*Mutina*) is 187 B.C., when the consul Aemilius Lepidus commissioned the construction of the via Aemilia, a consular highway that connected –and still connects– Rimini (*Ariminum*) on the Adriatic coast to Piacenza (*Placentia*) in the middle of the Po River valley. This strategic position enhanced the development of Modena as a Roman colony, founded in 183 B.C., and its urban layout reflected this role. Due to its origins, the area of Modena presents many interesting archaeological sites located in or near the city, as a sort of "widespread museum" (Luigini et al., 2019). Each site is jealous of its findings and discovered artefacts, which are rarely given to a unique location (e.g. the City Museum), but often retained in the territory. This fosters local cultural activities, and usually small dedicated museums are built. On the other hand, the distance

[1] ARCore by Google: https://developers.google.com/ar/discover

makes the fruition of artefacts difficult for both visitors and scholars. Visitors are unable to connect the entire history of Modena without moving around its territory, and in the same way, comparative studies may be hindered by these distances. This situation is common to many other cities and sites, both in Italy and abroad.

In the following sub-sections, we analyse some case studies, i.e. Roman artefacts located in different sites around Modena, and apply the proposed approach described in Section 2, developing 3D digital textured models and AR applications for an immersive experience and information integration.

3.1. The Roman mosaic of *Savignano sul Panaro* (Modena, Italy)

In 1897, an archaeological excavation in *Savignano sul Panaro* (near Modena, Italy) was promoted by Arsenio Crespellani, director of the Civic Museums of Modena at that time, following the discovery of the ruins of a large late Roman structure. The director was attracted by the exceptional floor mosaics, which were documented with polychrome watercolour paintings and drawings by the young artist Giuseppe Graziosi (Crespellani, 1899). However, in the late 19th century the mosaics were buried over in the same place, and were only uncovered during new excavations between 2010 and 2011, for the construction of a roundabout. Thanks to Graziosi's watercolours, the ruins of the architectural complex were identified by the Archaeological Superintendence of Emilia-Romagna, and new archaeological investigations were performed by identifying four rooms, one of which corresponds to the one described by Crespellani with letter A (the most important room, at least in this sector of the building). The Roman mosaic of the floor in room A, dated to the 5th century circa A.D. (Maioli, 2013), was removed for restoration. The Roman mosaic originally measured about 6.90 x 4.50 m, but less than half of its original surface is preserved. The use of polychrome stone and terracotta tiles combined with emerald green and ruby red glass tiles may reveal the client's wealth. Its decorations are intertwined elements, geometric and stylized plants that alternate with Solomon's knots, with a central element framed by a laurel wreath that borders a figurative decoration that is perhaps symbolic in nature. The mosaic is analysed in Corti (2001), Maioli (2013), Santachiara, Gherardini, & Leali, (2018).

We selected the Roman mosaic as a case study not only due to its archaeological relevance but also its current location. After restoration, in 2012 the mosaic was temporarily exhibited in the Civic Museums in Modena (Fig. 2a) in a suitable location for analysing and exploring its details. Then it was returned to the original area, installed permanently at the "Casa Natale Giuseppe Graziosi" (Savignano sul Panaro (Modena, Italy)) as a tribute to the painter who first documented its existence. However, the small room in which it is installed presents two main issues. The first concerns the visitors: it is not always possible to observe the mosaic from a viewpoint that shows its entirety, nor is it possible to reach the areas and details in the areas farthest from its boundaries (Fig. 2b). The second concerns the scholars: due to the small size of the room, and in order to let the mosaic be visible from the outside the building, the mosaic support lies at an unnatural inclination in relation to the floor, which causes great distortions when taking photos of the details and the overall geometry, as well as less-than-optimal lighting conditions and reflections on the surface from the windows.

(a)

(b)

Figure 2: a) The first location (after restoration) in the Civic Museums in Modena (source: http://mostreemusei.sns.it); b) The final location at the "*Casa Natale Giuseppe Graziosi*" in *Savignano sul Panaro* (Modena) (photo credits: Marianna Grandi, Italy).

To tackle these issues, we applied the proposed approach to the Roman mosaic in order to eliminate all viewing and space constraints. The 3D digital model of the Roman mosaic may be shown by AR on any floor, allowing you to walk on it, zoom in on its details, and so on.

The approach was applied to the Roman mosaic in two steps. First of all, a photogrammetric model of the Roman mosaic in *Savignano sul Panaro* was produced by means of 115 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). The Meshroom free and open source software performed the image-based reconstruction (Fig. 3). Then the 3D model was imported into Blender, a free and open source 3D modelling software, for mesh decimation and post-processing. In Blender, the 3D model was also scaled to its natural dimensions using the sides of the inclined support (see Fig. 2b) as references, the dimensions of which are known. The final model consists of a detailed textured 3D model of the mosaic, which allows the visitor to observe and perceive the third dimensions of artefacts (i.e. the arrangements of the tiles, their edges, some planar issues due to its state of preservation, etc.).

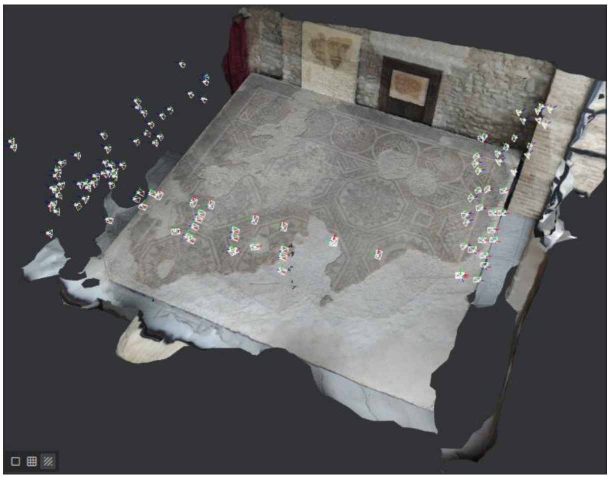


Figure 3: The 3D textured model as reconstructed in Meshroom, showing the camera positions of each photo used for the image-based reconstruction.

Secondly, the AR application was implemented on the Unity3D engine platform (Unity Technologies) by means of an ARCore plug-in.

The application may be implemented by using the ARCore library objects in the scene, working on the code that makes them work together (ARCore by Google, freeCodeCamp[2]).

- Step 1. Import the ARCore plug-in package into the Unity3D platform.
- Step 2. Detect suitable planes and track the real world, in order to set up the scene where the 3D models are to be placed. A Scene is a place where all the 3D objects are rendered. The planes are used as a reference for the model visualization.
- Step 3. Once ARCore has detected a scene (a suitable plane), the user can import the 3D models to be rendered on the screen by tapping the screen. When a user taps the screen, an object is instantiated where the user has tapped. This creates an anchor, which keeps the object in the same position in relation to the real world. The renderable object is attached to the scene and displayed to the user.
- Step 4. The camera position is used to adjust the object transformation so that the object appears to "look" at the camera from its position. The object transformation links the tapped anchor so that the object remains where the user has placed it, while moving the mobile device around.

The AR application is very user-friendly, and requires the user to: 1) frame a flat surface, e.g. the floor of the room, with the device camera, 2) tap on the device screen to position the AR scene, 3) move and walk around the scene as if it was a real environment.

The AR visualization of the mosaic was enriched by annotations, and other 2D and 3D digital objects. In this case, we integrated the visualization with a high-resolution photographic image (dimensions: 4164x3688, 300 dpi) of Graziosi's original watercolour painting which is housed in the Civic Museums archives in Modena (Fig. 4, on the right), which represents an original source for the visualization of the missing parts of the mosaic and an image showing the original location of the mosaic on the floor of room A (Fig 4, on the left).

The AR application lets the observer walk onto the mosaic in the virtual environment and explore each area (Fig. 5).

Figure 4: AR environment of the mosaic with annotations and data about the mosaic: on the right, Graziosi's watercolour painting and, on the left, an image of room A.

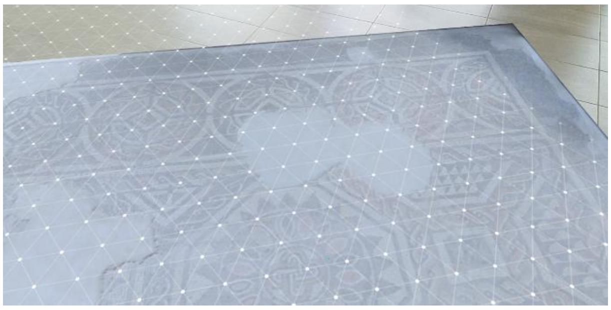


Figure 5: Details of the AR mosaic while walking on it.

3.2. Roman funerary lion sculptures in Modena

Two Roman funerary lion sculptures found in Modena were selected as case studies:

- The right one of the two Roman lion sculptures that flank the main door of Modena Cathedral, re-used as building materials during the construction of Cathedral of Modena.
- A lion sculpture from a funerary monument, now housed in the Museo Lapidario Estense (Estense Lapidary Museum of Modena).

In accordance with Roman law, the necropolises were located outside the wall of the ancient city of Modena. Most funerary monuments, such as sepulchres and memorial stones, were found outside the city gates, in particular along the Via Aemilia (Kleinhenz, 2004; Fields, 2018). However, archaeological remains from Roman times are no longer visible in Modena, even though some Roman artefacts have been reused and integrated into other monuments in later periods.

Our first case study deals with the right one of the pair of male lion sculptures flanking the main door of Modena Cathedral. They came from the Saint Lazarus necropolis (east Modena) and were probably part of the monumental tomb of a noble family (Kleinhenz, 2004). They were found around 1200 A.D. and then reused as building materials during the construction of Modena Cathedral (Rebecchi, 1984; Sandonnini,1983). Both are perfectly preserved.

[2] https://www.freecodecamp.org/news/tag/augmented-reality

The application of the approach leads to the development of a 3D model that is then augmented by the AR applications. Firstly, the photogrammetric reconstruction is performed using Meshroom software by means of 98 photos (Fig. 6). The photos were also taken with a Nikon P310. The result was a detailed textured model of the lion, which is then imported into the Blender software to remove the unnecessary parts and obtain the natural dimension of the lion sculpture. Then the 3D model was scaled in relation to a reference target object (i.e. a cube with known side length), which was positioned near the base (not shown in Fig. 6.a). We needed an additional reference as the stone base of the lion sculpture presents irregular surfaces with uncertain dimensions, and was therefore unusable for scaling.

The 3D model was then integrated into the AR application, and could be easily visualized and managed in any real environment. The steps previously described for the development of the AR application of the Roman mosaic were the same also in this case.

The second lion sculpture depicts a male lion and was located in the Museo Lapidario Estense, in the west span E, with number 52. According to (Malmusi, 1930, p.62; Giordani and Paolozzi Strozzi, 2005, p. 379). It can be historically placed in the first half of the 1st century A.D., and used as a decorative element belonging to an ancient Roman funerary monument. It is made from Vicentina stone from the Berici Hills (Vicenza, Italy) and was probably sent to Modena by rivers.

Similar lion sculptures can be found in other Roman funerary structures of the Augustan era, such as the contemporary ones of Sepino (Campobasso, Italy) and Aquileia (Udine, Italy). In accordance with these monuments, this sculpture was probably one of the four lions guarding a monumental sepulchre built along the ancient consular road “Via Aemilia”.

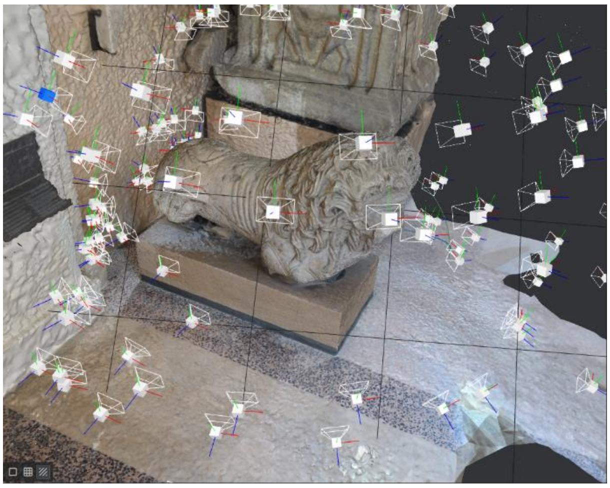
Although damaged, the lion statue appears in excellent condition: the lion is represented in the frontal position, the muzzle turned slightly to the left side, from the viewpoint of the observer. The sculpture is installed on a base measuring 620 x 1400 x (height) 345 mm.

Similarly to the previous case, the 3D reconstruction was performed using Meshroom with 134 photos taken with the Nikon P310. The result is a detailed textured model of the lion (Fig. 7a), particularly on the back and bottom side. The textured model was then imported into the Blender software to remove the unnecessary parts and obtain the natural dimension of the lion sculpture.

(a)

(b)

Figure 6: The 3D model of the Cathedral lion obtained using Meshroom: a) before, and b) after the post-processing operation to remove the unnecessary parts.



(a)

(b)

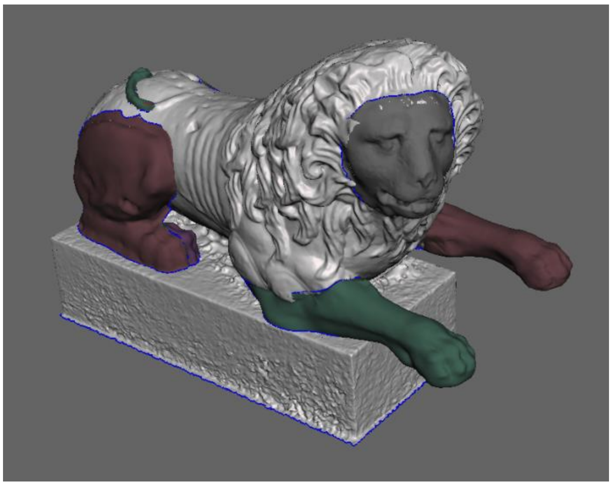
Figure 7: The 3D model of the damaged lion obtained using Meshroom: a) before, and b) after the post-processing operation to remove the unnecessary parts.

We scaled the model in relation to its support, which is a perfect parallelepiped with dimensions that can be accurately measured (Fig. 7b).

However, as many details were missing, we decided to integrate these parts with the damaged lion sculpture model, by modifying the texture and by partially re-modelling them using the Meshmixer free software (Autodesk). The additional parts had to be scaled, cut, refined and smoothed: the two final 3D models are shown in Fig. 8 and were used for the next phase of AR implementation. For these purposes, we digitally reconstructed in 3D another lion sculpture, although not found in Modena, a crouching funerary lion of the 2nd century A.D., housed in the Capitoline Museum of Rome (Italy). The missing parts were also taken from the right cathedral lion described above.

The direct comparison among these three models suggests two different positions of the lion body: the lion may 1) have a crouching position, or 2) stand on its four legs. We developed both of them, though focusing on the crouching position shown in Fig 8, we extracted the following parts:

- from the Cathedral lion, the muzzle, according to (Rebecchi, 1984; Sandonnini, 1983),
- from the crouching funerary lion of the Capitoline Museum, the front and hind legs and the tail end.



(a)

(b)

Figure 8: The 3D model of the damaged lion after integration with some of the missing details, according to a possible reconstruction: a) The mesh of each added detail in Meshmixer; b) The textured model.

Although this is only a first hypothesis, according to some of the authors, we can state that this approach is able to support this activity of virtual restoration, by visualizing and sharing the reconstructed model with other people at the same time. Again, the difficulty of physically comparing distant artefacts may be overcome by the proposed approach which, by integrating 3D and AR models, allows for their direct comparison (as in the case of the damaged lion and the preserved one) in order to support scholars and researchers in evaluating different hypotheses (Fig. 9).

(a)

(b)

(c)

Figure 9: The final visualization of all the lion sculptures within the AR environment: (a) The cathedral lion and the damaged lion, (b) the same lions while walking around them, (c) the visualization of the damaged lion and its reconstruction.

Finally, the application was tested with visitors and museum experts both inside and outside the Civic Museums in Modena (Fig. 10). The test was conducted with 26 users, eight of whom are museum experts (curators and archaeologists). During the test, the app was run on two Android devices (i.e. a 6'' mobile phone and a 10'' tablet), and the users were asked to use the app by themselves, after a brief introduction about its use.

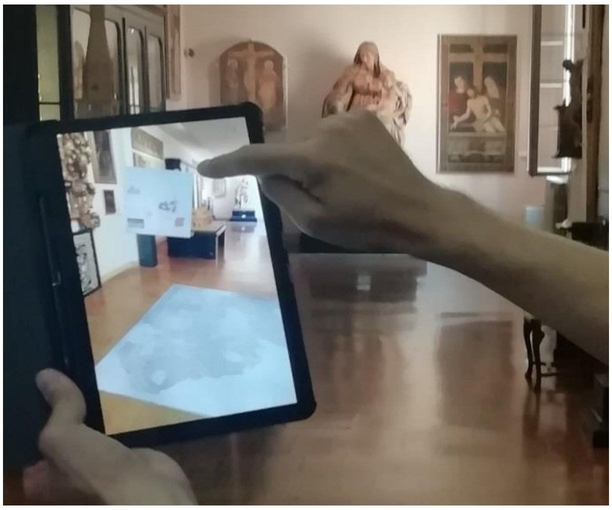


Figure 10: Testing the app in the Civic Museums in Modena.

While testing the app with museum users, the most frequent comments related to their preference for the smaller device (judged as more comfortable to handle) and whether the app could also run on head-mounted displays (HMD, e.g. visors). Conversely, the main perceived drawback lays in the users' attempts to zoom in on the artefact using their fingers on the screen (like they would with an image on the mobile phone) instead of moving closer to the augmented artefact as if they were real: every time the users touched the screen, the whole AR scene re-positioned to the clicked point. In order to evaluate the users' experience with the app, a brief survey was conducted among the users. The questions and the results are collected in Table 1.

Table 1. Results of the users' experience with the app.

Question	*Visitors*	*Museum experts*
1. Is this the first time you have used a museum app?	Yes 80%	Yes 25%
2. Can the app enhance your fruition of the artefact?	Yes 100%	Yes 100%
3. Give a score to your experience with the app, from 1 (very insufficient) to 5 (very good)	3.80	3.87
4. Would you pay to use/have this app?	Yes 80%	Yes 87.5%

The survey asked the users to provide feedback on their previous experience with museum apps (question 1), their experience with our app (question 2) by requiring comments about the pros and cons after testing the app, a global score of their experience with the app (question 3), and if they would pay for using (as a visitor) or having (as museum experts and personnel) the app.

The first answer shows that most visitors have no previous experience with museum apps while, as we can expect, the museum experts are used to such technologies.

All the users assessed the app as useful for enhancing the fruition of the artefact (question 2) but with different approaches. In the free comments, the common pros include: "better understanding of the artefact", "to note more details", "mixing various locations at the same time in one place", "you can see things that are not there", "visitors can try new technologies dedicated to cultural heritage", "interactivity with the artefact otherwise not possible", "add multimedia contents". Conversely, many cons are highlighted in relation to a generic museum app: "real artefacts cannot be replaced by virtual ones", "usability for the visitor without instructions", "the augmented object hides the real world". Specifically to our app, users highlighted the following cons: "cannot use the touchscreen", "some models require more details", "adjustment to lighting", "it needs large spaces" (in relation to the mosaic that is in natural size), "the floor grid is superimposed on the mosaic", "the texture of the reconstructed lion is unnatural".

Then, the global score for the experience with the app was then assigned by the users. For this purpose, a 5-point Likert-type scale was used, from 1 (very insufficient) to 5 (very good). The results show the same average score assigned by both user categories, which can be interpreted differently in relation to the first answer. Most of the visitors had never tested a museum app before, so the final positive score for our app may originate from novelty and surprise, as we can read in the free comments (e.g. "A new way of museum fruition" or "I can create a museum at home"). On the other hand, the positive average score assigned by the museum experts demonstrates its suitability in a museum context. In particular, many comments refer to the possibility to provide more information to visitors without affecting the actual museum layout, or to show the artefacts stored in museum warehouses due to lack of exhibition space.

The purpose of question 4 was to check if users really appreciated the app, recognizing it as an added value for the museum visit. Most of the visitors agreed on the idea of paying an extra fee for the app, "like an audio guide", although someone proposed to include it in the ticket price. Similarly, the museum experts stated that the app should be provided to visitors free of charge to better respond to their needs.

After the test, we edited the app in accordance with the users' suggestions, implementing the following customizations:

1) In addition to the prefab of the ARCore kit, we added a module to manage the display of the planes recognized with the Simultaneous Localization And Mapping (SLAM), to prevent them from being displayed once the model (e.g. the lion) has been added to the scene. In order to achieve this result, we created a static class that stores the display status (Fig. 11), whose variable is modified when the 3D models are instantiated, and referenced by the DetectedPlaneVisualizer and DetectedPointVisualizer classes that switch visibility accordingly.

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using GoogleARCore;

public static class DetectedPlaneToggler  {

    public static bool planeVisible = true;
    public static float Yangle = 0;
}
```

Figure 11: Static class coding lines.

2) Regarding the correction of environmental lighting conditions, we adjusted the brightness of the object by sampling the value taken from the ARCore class EnvironmentalLight, through which it is possible to read an estimated value of the frame light (Frame.LightEstimate.ColorCorrection).

This value, in vector format R, G, B, is then converted into a grayscale value, i.e. a single float value.

This value lends itself as an ideal multiplier of the albedo value for any material present in the scene (as in the case of the lions), thus obtaining the illumination of the materials consistent with the video stream frame.

4. Discussion and conclusion

This paper proposes a framework for integrating 3D virtual models and AR techniques for enhancing the fruition of museum artefacts. The 3D model of a real artefact is first developed by means of image-based techniques, including close-range photogrammetry by means of standard images and free and open source software. A pre- and a post-processing phase deals with image selection and editing, and then the point clouds are cut and decimated in order to make the 3D model more suitable for the next phase.

In the AR implementation, we use a Unity3D plug-in, namely ARCore for building AR applications, working with native Android devices using the Java programming language. The final result is a custom Android application able to visualize an artefact in the real environment in real time, offering users an immersive experience of the artefact even when not actually in the museum. The AR artefact can be managed, analysed, observed and zoomed in on like a real object, and by many people at the same time.

The approach was tested and positively assessed by museum experts and visitors on selected case studies, Roman artefacts found in Modena and now located in various locations across the Modena area. In the first case, a Roman mosaic was shown and compared with a reference painting, with the aim of supporting the analysis of the incomplete mosaic pattern.

In the second case, two funerary lion sculptures were real-time visualized in the real world. In particular, the damaged lion sculpture was firstly digitally reconstructed and integrated with the missing parts extracted and remodelled from other sculptures, and then visualized in one of its hypothetical positions.

Some drawbacks of the framework include:

- Due to the image-based approach for capturing 3D artefacts, e.g. photogrammetry, the lighting conditions may be a critical point in the approach, which requires post-processing of the images in order to achieve better results. Again, the accessibility of the artefact represents a weak point of the approach: in the specific case of the Roman mosaic, the small room in which it is installed causes significant distortions when taking photos of the details and the overall geometry, so it requires accurate image pre-processing before 3D reconstruction.
- The selection of the “missing parts” requires the study and investigation of models with similar characteristics, according to art history and archaeological studies. The reconstructions proposed in this paper may be considered as simply an example in order to test the approach capabilities.

The pros on the other hand include the use of AR to support the analysis of the artefact by means of interactions with users (e.g. visitors, scholars, researchers, etc.), and works as an educational tool able to guide the understanding of what they observe.

The approach is able to support the comparison of artefacts by overcoming space and time constraints. If the artefact cannot be physically moved from one site to another, 3D digitization and AR can eliminate distances. This is a positive result for artefacts located in different locations, as in the case of the city of Modena. In fact, due to its origins, the Modena area presents many interesting archaeological sites located both in the city and in the surrounding area, acting as a sort of “widespread museum”. This situation is common to many other cities and places both in Italy and in other countries, so the approach can be positively extended to other similar situations.

Again, the proposed AR application does not require the use of markers, but is based on tracking the natural features of the real environment. Therefore, the AR application requires only the detection of a planar surface (e.g. the floor, a table, etc.) on which to locate the virtual 3D model.

In accordance with visitors’ suggestions, future works could focus on the creation of a version to be used with a HMD, in order to improve the level of user immersion.

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Photo credits

All images are by the authors unless otherwise noted.

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