AR AND VR FOR ENHANCING MUSEUMS’ HERITAGE THROUGH 3D RECONSTRUCTION OF FRAGMENTED STATUE AND ARCHITECTURAL CONTEXT

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ABSTRACT:

This paper presents the results of multidisciplinary research in which reconstructive digital modelling operates on different areas of heritage and at different scales to realize an analysis, interpretation, and communication experience in the field of museum valorization. It is, in fact, a work that includes both the philological reconstruction of the lost parts of a Buddha statue of Gandhāra, dating back to the second century b.C. and kept at the Museum of Oriental Art (MAO) in Turin, and its contextualization within a coeval architectural complex, recognized as philologically compatible, located in Balo-Kale, in the region of Gandhāra. The reconstructive models are finally used with communicative purposes for augmented reality (AR) and virtual reality (VR) applications inside the museum.

1. INTRODUCTION

This proposal presents the results of multidisciplinary research in which reconstructive digital modelling operates on different areas of heritage and at different scales to realize an analysis, interpretation, and communication experience in the field of museum valorization. It is, in fact, a work that includes both the philological reconstruction of the lost parts of a Buddha statue of Gandhāra (fig. 1), dating back to the second century b.C. and kept at the Museum of Oriental Art (MAO) in Turin, and its contextualization within a coeval architectural complex, recognized as philologically compatible, located in Balo-Kale, in the region of Gandhara. In the first century b.C., Gandhāra reached the height of its artistic splendour, as a meeting place between the contents of Buddhist sacred art and a cosmopolitan language characterised by the coexistence of classical (Hellenistic-Roman), Indian, Iranian and Central Asian influences. The statue of Buddha, made of grey schist, shows the left knee slightly bent in the act of taking a step forward and is missing the legs, forearms, and part of the nimbus. The position of the hands has been philologically hypothesized: the gesture of the left hand holding a hem of the *samghāti* (winter monastic robe) and the *abhayamudrā*, the gesture of fearlessness (the right hand is held upright, and the palm is facing outwards).
The reconstructive models are finally used with communicative purposes for augmented reality (AR) and virtual reality (VR) applications inside the museum.
The entire work is oriented towards the use of Free and Open Source Software (FOSS) and low-cost mobile devices for personal use.
The pipeline is articulated in the operative phases related to the statue, through acquisition, modelling and digital reconstruction, and to the architectural complex, through the representation of the archaeological surveys and modeling of the environmental context.
Lastly, recognition and anchoring operations have enabled the activation of AR and VR experiences.

Scholars experts in archaeology and art history of Gandhāra, in digital representation techniques and in information processing systems collaborated for the realization of the research, which was carried out within the framework of the agreement between the Fondazione Torino Musei and the Department of Architecture and Design at Politecnico di Torino, aimed to the enhancement of the cultural heritage of the Museum of Oriental Art in Turin through its digitization, 3D modeling and application in VR and AR programs, with the support of the VR@POLITO lab, and through physical modeling aimed at inclusive fruition of heritage, with the support of MODLab Arch and Design.

2. RELATED WORKS

The topics of virtual reconstruction and heritage communication must consider as the main methodological framework references the London Charter (2009), a general reference for computer-based visualizations of cultural heritage, and the Principles of Seville (2012), focused on the specific field of virtual archaeology. More recently, Pietroni and Ferdani (2021) articulated an extensive theoretical discussion aimed to clarify and define concepts, functions, fields of application, and methodologies related to virtual restoration and virtual reconstruction in Cultural Heritage. Moreover, Schäfer (2019) compared methods, techniques, and strategies of 3D digital modelling and reconstruction dealing with uncertainty visualization in archaeology.
Recent research that develops these issues on case studies from different disciplinary perspectives includes:
• Haynes et al. (2019), that showed a pipeline based on Terrestrial Laser Scanning (TLS) survey, virtual reconstruction, and visualization of sculptures and stupas belonging to Gandhāran art and architecture;
• Gherardini et al. (2018), that presented the photogrammetric reconstruction, 3D modelling, and AR experience of a stone lion preserved in the Museo Lapidario Estense;

Figure 1. Buddha statue of Gandhara, II century b.C., Museum of Oriental Art (MAO) in Turin.

• Clini et al. (2018), that aimed to enrich visitors' experience in real museum – the Roman Forum of Fanum Fortunae -, and implemented the paradigm of learning by interacting with innovative VR technologies;
• Toubekis et al. (2017), that showed the use of 3D digital modelling on partially destroyed Buddha figures in Bamiyan, through superposition on a detailed 3D laser recording, and set up an immersive VR experience aimed to become the basis for scientific re-assembly of the original fragments;
• Tefera et al. (2018), that presented on a web-based 3D imaging pipeline useful for 3D reconstruction starting from a set of images.

3. INFORMATION PROCESSING SYSTEMS FOR CULTURAL HERITAGE

Nowadays, information processing systems play a central role in many fields of our society, including cultural heritage. Digitization in particular is key to the envisaged evolution of the latter field, as the availability of computer-generated replicas of physical elements (being them either paintings, statues, ruins, etc.) opens up an amazing number of opportunities for the protection, conservation, restoration, research, dissemination and promotion of precious cultural assets.
A cornerstone in the digitization process is represented by the means that can be used for the production of digital replicas, which encompass core enabling technologies like laser scanners and camera sensors for, e.g., 3D photogrammetry applications. Technologies for 3D reconstructions are getting commonplace in the consumer market (Cappelletto 2016), approaches to automate and industrialize the digitization of cultural artifacts in a quick and inexpensive way have already been proposed (Singh 2014), and large repositories containing high quality models created, e.g., in the contexts of public-funded projects or

Figure 2. Photographic set in the hall of Indian art at MAO. On the left the Yaksha, on the right in background the standing Buddha of Mathura.

by no-profit organizations are now available (Champion 2020). Some museums are also making their collections entirely available in the form of digital models, fostering further research in the field.
Digital copies are often leveraged, e.g., to implement virtual visits, a kind of cultural heritage-oriented application of a fast spreading paradigm know as digital twinning (Marra 2021). This way of making remote cultural heritage sites accessible is not new, as preliminary examples date back to several decades ago now (Wilson 1998). However, technological advancements in the digitization steps allow today the creation of ever more realistic reconstructions. It is worth noting, though, that technology progressed not only on the acquisition side, but also on the fruition, i.e., the end-users, side. In fact, early examples in which remote visits were based on images and video content are today complemented by largely immersive experiences leveraging AR and VR technologies, today often referred to also with the similar or combined concepts of mixed reality (MR) and extended reality (XR) (Bekele2018).
With VR, the users (visitors, in this case) can be immersed in a fully digital environment, in which they are allowed to move and interact with virtual objects and, possibly, with other users. With AR, in turn, it is possible to augment the experience of users physically co-located with the real artifacts, who can see digital content added or overlapped to the real ones, e.g., through the screen of a portable devices, the lenses of a wearable headset or within a holographic case (Spallone et al. 2021).
This type of experiences is getting incredibly relevant today, since they are able to alleviate the effects of closures and restrictions related to the pandemic situation (Vayanou 2020), as well as contribute to reducing emissions, thus fostering so-called sustainable or green tourism (Bijlani 2021).
Other information processing technologies could certainly be mentioned in this context, like big data (helpful, e.g., to study visitors' interests and flows), blockchain (e.g., for managing security aspects about assets property and fighting frauds), additive manufacturing (e.g., to enable the fruition of content by people with certain disabilities), etc. However, another technology that is truly essential for the implementation of remote visits and, more in general, of next-generation cultural heritage applications is represented by mobile networks, which promise to guarantee, e.g., with forthcoming 5G and 6G infrastructures, high bandwidth and low latency connectivity anywhere and anytime, which is an essential prerequisite to develop effective digital twins (Gao 2021).
Network-related challenges pair with further open issues that characterize the digital fruition of cultural assets, which pertain, among others, the level of fidelity as well as the sense of immersion and presence that can be experienced in hybrid virtual-real or virtual-only environments. In this perspective,

further developments will be needed to support a proper embodiment of the user in terms of his/her and other users' avatar-based representation, naturalness, and intuitiveness of human-computer interfaces and, most importantly, storytelling aspects (Qu 2020).

4. DIGITAL STORYTELLING: PATHS THROUGH BUDDHIST ART

In recent decades, digital technologies have been increasingly used to present cultural heritage. Detailed 3D reconstructions offer the user the possibility to travel through time in an immersive way. Digital storytelling enriches these experiences with information about the context, events and characters related to the object.

These tools help remove time-space barriers and offer a more immersive and personalized visit to the user. Handler Miller defines digital storytelling as the use of digital media platforms and interactivity for narrative purposes, either for fictional or for non-fiction stories. Interactive digital stories, through a combination of museum collections and digital content, become parts of museum exhibitions, virtual and augmented reality applications and, of course, serious games (Rizvic et al., 2020).

In this specific case, the selected artworks are part of the exhibition of Indian art located on the first floor of the MAO (fig. 2). The experience proposed in this paper is part of a broader path focused on the evolution of anthropomorphic images in the Buddhist religion. The path aimed to communicate this content includes four artworks: a Yaksha, a head of a Kapardin Buddha and two standing Buddha, from Mathurā and Gandhāra regions.

The communication uses AR visualization and an avatar as a virtual guide, whose studied pointing technique reinforces the verbal language. AR experience and the virtual guide accompany visitors through the entire itinerary. VR is used for immersive experience where the artwork is The path starts with a Yaksha made by stone (yaksha are sylvan semi-divinities associated with the cult of the tree, as well as figures of protectors of the place, sometimes with an evil character). The yaksha are the first anthropomorphic cult images to be depicted in Hindu, Buddhist and Jain contexts. The statue at MAO is one of the first examples of the Kushāna art (that between the first and third centuries a.C. elaborated the first representations of Hindu divinities) of Mathurā, where one can observe the search for naturalistic component in the delineation of muscles and ornaments. The statue is missing its head and arms, which have been digitally reconstructed, following the photogrammetric acquisition of the artwork and the philological comparison with a Bodhisattva of Mathurā at Cleveland Museum of Art for the integration of the fragments.

Then, the large head carved in spotted red sandstone of Kapardin Buddha (from *kaparda*, characteristic shell hairstyle) belongs to the same Kushāna art of Mathurā and is one of the earliest depictions of the divinity. It has rigid facial features and its detached expression is rendered with the fixity of the globular eyes. For the reconstruction of the body, after evaluating the alternative between the standing position and the seated one in the lotus position, the latter has been chosen. The Stele of Katra at the Government Museum of Mathurā was taken as a reference and was also used for the 3D reconstruction of the hypothetical sculpted high relief that acts as a backdrop.

The third step is a sculpture of a standing Buddha made-up by red sandstone, one of the best examples of the Gupta art (from fourth to sixth century a.C.) of Mathurā.

Figure 3. The terrace of Gumbat (GBK I). View from N (2011).

Figure 4. The shrine before excavation after preliminary restoration (2011). View from NNE.

In the statue appears the new refined style, pervaded by an idealized naturalism that imposes itself for the spirituality of the image. This statue has lost its forearms, legs and part of the nimbus, which have been reconstructed by referring to two standing buddhas respectively kept at the Government Museum of Mathurā and the Freer Gallery of Art, Washington, DC, U.S.A. The last artwork of the tour is the standing Buddha from Gandhāra, the subject of the developed case study. In this region Buddhist art with a cosmopolitan language was established between the second century b.C. and the fifth-sixth centuries a.C.

The digital storytelling complements the traditional one (panels and audio guides). The story is developed on two levels: the more general one that represents the thread between the various works and the one related to the single work connected to its contextualization and reconstruction of the missing parts.

Digital tools were then used on the one hand to provide keys to understanding the missing parts and the related different reconstructive hypotheses, able to deepen the research and generate debate. As seen, for each work, a 3D reconstruction has been planned, starting from iconographic documentation related to similar and contemporary works from other museums, thanks to the contribution of Claudia Ramasso, curator of MAO, and Luca Maria Olivieri. The missing parts, according to the principles of digital archaeology, have been modelled without the application of textures to ensure the distinguishability of the original part and the reconstruction.

5. THE “GUMBAT” BALO-KALE AND THE BUDDHA OF GANDHĀRA AT MAO

The site of Gumbat (Pashto for ‘stupa’) is located at the center of the Kandak valley (Swat, Pakistan), on the left side, at an

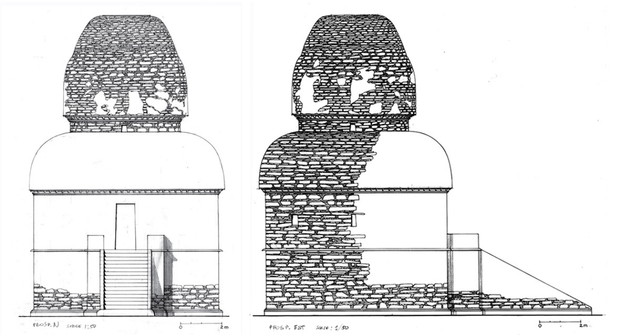

Figure 5. North and East elevations of Gumbat (after the end of the excavations; 2011).

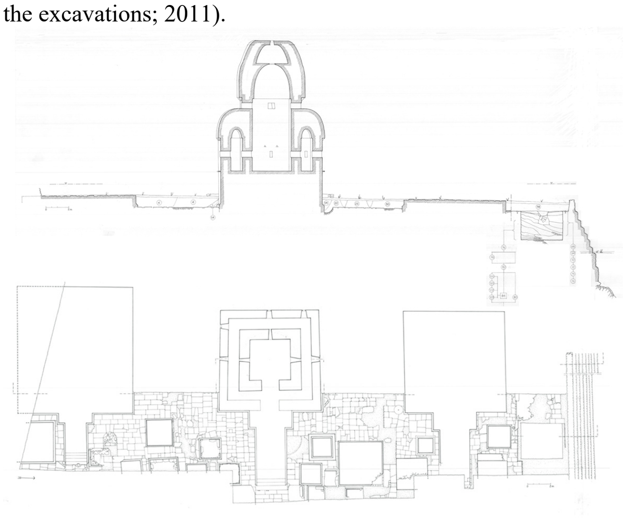

Figure 6. Gumbat: The archaeological area of GBK I. Cross-section and plan (after the end of the excavations; 2011).

altitude of approx. 986.00 m asl., at ca 5 km south of the archaeological site of Barikot, the ancient city known as Bazira or Beira by the Alexander’s historians.

In 2011 and 2012 the site was excavated, and its main monuments restored by the Italian Archaeological Mission (IsIAO/ISMEO, now with Ca’ Foscari University of Venice) and by the Provincial Directorate of Archaeology and Museums, Govt of Khyber-Pakhtunkwa, under the vigilance of the Department of Archaeology and Museums, Govt of Pakistan. The site covers an area of approx. 14,000 m2 and can be subdivided in three terraces.

The monument standing at the centre of Terrace I (fig. 3) is a Buddhist domed shrine (Great Shrine) one of the most interesting and best-preserved ancient monuments of the Swat valley. Originally hosting a relic, cult statue or votive stupa, the Great Shrine has a partially preserved double dome, rising on a monumental platform in a beautiful mountain scenario (Meister, Olivieri and Vidale 2016, Olivieri 2021, Olivieri and Iori 2021).

It is a shrine-category chapel with a square plan and enclosed cloister set on a high podium; its entrance lies to the E (fig. 4). The external walls are separated from the inner cells by a vaulted corridor with windows (one each on S, W, and N sides). This cloister is covered by a sloping lower roof supported by a row of cyma reverse-type brackets. The square sanctum chamber rises through a cylindrical necking (with slit windows) above the cloister roof, supported by a row of cyma reversa-type brackets, culminating in an oval-outlined dome (figs. 5-6).

The external ovate dome is thus actually formed by a superimposed double vaulting, a major architectural peculiarity of the monument (Harle 1994). The upper part of this oval vault - which was still visible during Stein’s field research - is missing, and the present external dome ends with a flat

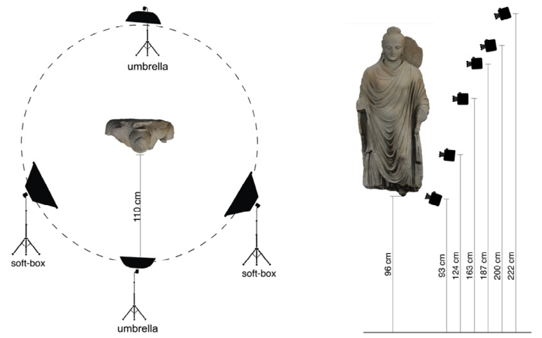

Figure 7. Photographic shooting carried out on the Gandhāra Buddha: plan and elevation points scheme.

Figure 8. Photo alignment with sparse cloud.

horizontal surface. Most probably the missing part was made of perishable materials heavily plastered on the exterior.

Considered for years a late monument because of its characteristic double dome, against this trend went Faccenna (2006) who proposed an early-1st century b.C. chronology on the basis of the absolute dates and archaeological context.

The Great Shrine was supposed to host stupa-reliquary (Behrendt 2006), or a large votive stele or statue, ‘modelled in stucco’ as suggested by Stein (1930).

We do not know what the object of worship actually was, as no traces of either a stupa or a podium for a statue were found during the excavation of the cell.

Certainly, the hypothesis of a statue suggested by Stein is weak in this case, but it would have been perfectly plausible if (a) the cell had been smaller in size, and (b) had had a free rear wall.

For these reasons in this reconstruction, we wanted to play both on the dimensions, imagining the cell and the whole monument smaller, but more or less with the same proportions, and on the back wall, eliminating the niches, so as to insert inside a statue in schist of less than natural size. We imagine the statue placed on a podium leaning against the back wall, perhaps flanked by others, or isolated, as a statue-stele, according to a compositive model in vogue since the middle of the 3rd century CE in Swat.

For the hypothesis we suggested a potentially coeval Gandharan statue representing a haloed standing Buddha draped with his *samghāti* housed at the Turin Museo di Arte Orientale. The statue is quite interesting for this specific context, because it seems to have been sculpted to see it from below (note the slight distortion of the face when viewed from the front).

6. DEVELOPED METHODOLOGY

The pipeline of the digital reconstruction process within the museum sculptural heritage is already consolidated. In the presented case study which, as said, is part of a larger project, the acquisition was made using the well-known Structure from Motion (SfM) technology. It was designed considering the

immovability of the statue, the non-optimal lighting conditions, and the presence of reflections due to the surrounding exhibition.
The Gandharan Buddha stands in the centre of the room, measuring 119 cm in height plus the 96 cm pedestal. The equipment consists of a digital camera Canon EOS 40D with Canon EF 50mm lens, a tripod, and a set of lights. The statue was illuminated with two soft-boxes placed three-quarters symmetrically with respect to the front, while at the back it was placed one lamp coupled with reflective umbrella (figs. 7-8).
Before proceeding with the survey, the shooting mode, the distance of the camera, the number of turns to be made around the artwork and the approximate number of shots for each turn have been established. Considering the position of the artefact and the properties previously illustrated it was decided to set the shots with the 160 ISO and aperture priority of 8f, the exposure time varies between 1/5 of a second to 2.5 seconds.
A total of 118 shots were taken around the statue at about 1.10 m at six different heights, making sure to have at least a 60% overlap between consecutive shots (Table 1). To move with more precision, a trajectory as circular as possible was traced on the ground, keeping constant the shooting distance from the vertical axis of the work.

Set of photos	**Shooting height [m]**	**GSD [mm/pixel]**
Set 1	0,93	0,243
Set 2	1,24	0,325
Set 3	1,63	0,427
Set 4	1,87	0,489
Set 5	2,00	0,523
Set 6	2,22	0,581
Medium value		**0,431**

Table 1. Calculation of ground sample distance.

The acquired data were processed using Agisoft Metashape®, through the following steps: image alignment, creation of the sparse and dense point clouds, surface/mesh and texture generation (figs. 9-10). The mesh model was finally exported in .obj for the implementation within Blender® environment.
The latter tool was used for texturization and rendering, as well as for the integration of the missing or fragmented parts – the forearms, the legs in the part uncovered by the robe, and the nimbus – through 3D modelling with sculpting techniques. The DAZ Studio application was employed as a support for the reconstruction of the forearms, whereas the legs and the base of the statue were reconstructed by analogy with another Buddha of Gandhāra kept at the Minneapolis Institute of Art, whose scan is available on the Sketchfab platform (figs. 11-12).
A further reconstructive modelling operation concerned the setting of the statue in the Gumbat cell mentioned above. The volumetric model of the building was realized based on the scale drawings of the mission in Swat (figs. 5-6), as above detailed, completed with some decorative details found on the artefact (fig. 13). These are the so-called stair-risers, or decorations of sacred scenes and symbols related to the life of Buddha carved in bas-relief in the riser of the steps. The last step has a continuous band decorated with a pipal plant whorl, the rest of the staircase probably has symbols placed at the sides and in the middle and repeated in sequence. The creation of the building materials required the use of high-quality textures, downloaded in 4K quality from the AmbientCG and PolyHeaven sites, combined with each other and modified within the shader editor of Blender®.

Figure 9. Sparse, dense cloud, mesh model, textured model.

Figure 10. Optimized 3D model of the Gandhāra Buddha derived from Metashape® software.

Figure 11. Optimized 3D model of the Gandhāra Buddha derived from Metashape® software.

After setting up the materials for each mesh of the building, we proceeded with baking, in order to obtain images without the set-up of the nodes, for more versatility in controlling the shaders in the following steps. Then, the Great Shrine was inserted in the original environmental context thanks to the Blender GIS add-on and flanked by two stupas in the conformation assumed by Olivieri. The selected area included the mountains surrounding the archaeological site. In order to preserve the realistic qualities of the terrain, the scene was converted into a 360° HDRI image that could be used as a background for the 360° render in Blender, while the terrain in direct contact with the architectural complex and in its vicinity was modelled using sculpting techniques, attempting to reproduce the characteristics of the terrain documented in the photographs of the Swat mission.
All the reconstructive phases were supported by a rigorous work of philological interpretation, guided by Olivieri and Ramasso.
The communication process was articulated into AR and VR prototypal applications, not yet widespread in museum, where,

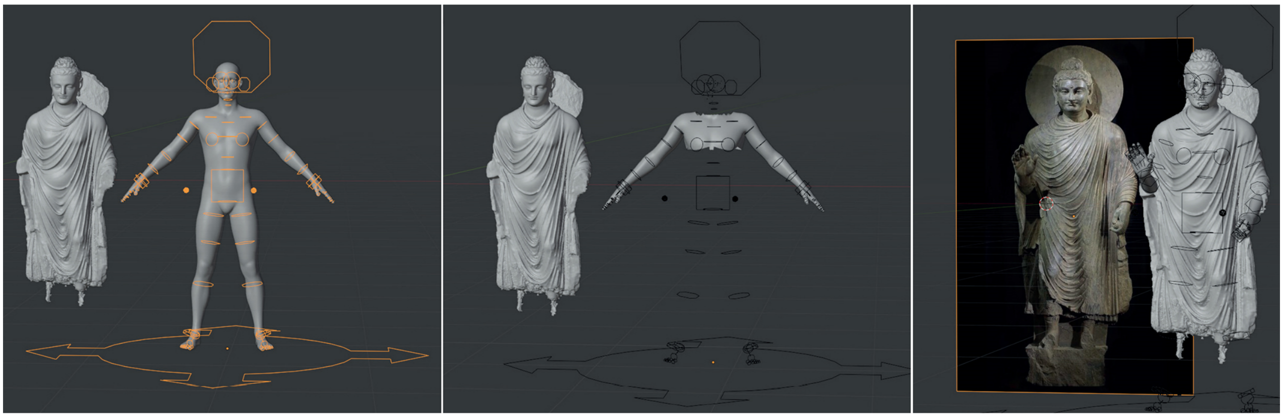

Figure 12. The mannequin posing and the integration of the forearms, referring to standing Buddha at The Metropolitan Museum of Art, New York, U.S.A.

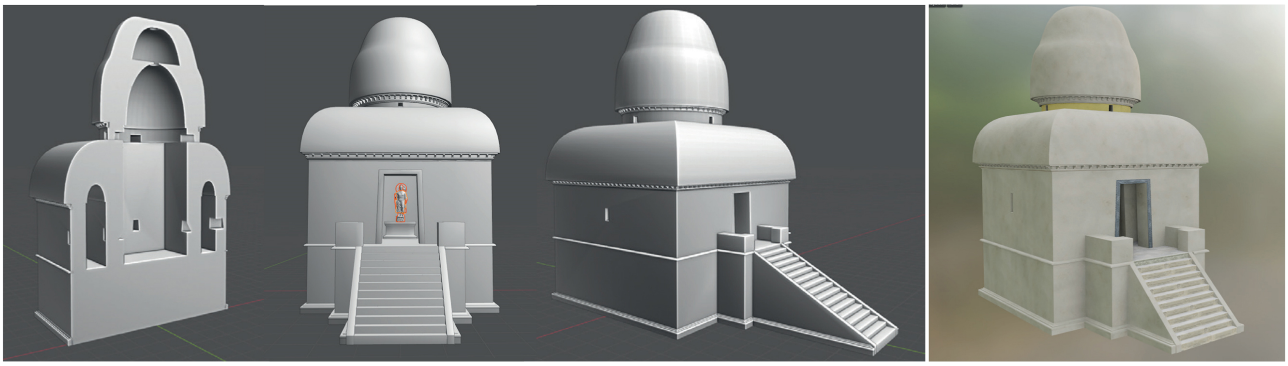

Figure 13. Reconstructive 3D model of Gumbat.

in most of the cases, audio guides with numeric keypads aimed at predominantly auditory fruition are adopted.

7. AR AND VR EXPERIENCES

The realization of AR and VR experiences took shape thanks to the use of Unity, integrating it with some additional tools such as Vuforia, Google VR and Bolt.
The digital model of the statue was loaded into the Model Target Generator, one of the applications provided by Vuforia, which transforms a 3D object into a 3D target and provides a guide view to help during the framing phase. In this way the target in AR experience is the statue itself.
The project is developed for mobile devices, so that the user can easily install the app on his own smartphone Therefore, to start the experience, the statue needs to be framed by the camera inside the guide view from the right angle. As soon as the software recognizes the statue, the 3D model is activated and it exactly overlaps the real one, following all the camera movements. After an introductive speech about the statue, in the next step the reconstructions of the destroyed parts of the statue appear. During the experience, the user can select the reconstructed parts, marked in white, by clicking on the touchscreen. By doing that, a detailed description of the specific item appears: the selected item turns red, and an audio track starts while being transcribed on a text panel. The simple user interface shows a few buttons, to play and pause the audio, to expand and close the text panel, and to return to the first step of the experience (fig. 14).
The development of VR app is also intended for the installation on smartphones, using Google Cardboard as a viewer. The experience offers the possibility to observe the statue inside a philologically compatible context. Wearing the viewer, the users are placed in front of Gumbat and can move around for a virtual tour. Since there are no input devices other than the smartphone inserted in the viewer, only one type of input can be given, translated into a click in correspondence with the cursor placed in the center of the screen. With the gyroscope users can observe the surrounding landscape and look at the interactive elements placed in the scene, including some arrows: by positioning the cursor over them and clicking, the camera viewpoint moves in the desired direction. When the users are in the central cell, they can click on the various parts of the statue and, similarly to what happens in the AR app, audio tracks provide some explanations about the selected details. It is also possible to perform the ritual walk around the temple and gather information on some architectural details, while a background traditional local music is played.
In both experiences, handled by a real time engine, a programming phase in C# language has been required to manage user interactions (fig. 15). Thanks to an additional tool such as Bolt, scripting can be visually done through the set-up of nodes. The nodes translate the lines of code into a visual language and allows you to see how the script works in real time, following its flow both at start-up and during the update given by the inputs received. The functioning of the code is mainly based on the Physics Raycaster, which emits a virtual ray from the position of the touch on the screen, in the case of the AR app, and by the central cursor in the VR one. The ray travels through space until it collides with a certain type of 3D objects equipped with a component that makes them visible to the ray: depending on the type of the hit object, a series of actions are initiated, which can vary from the reproduction of animations and audio tracks to the activation or deactivation of certain elements in the scene and their movement (fig. 16).

Figure 14. AR experience with 3D reconstruction of the Gandhāra Buddha.

Figure 15. VR application visual script on Unity® software with Bolt® plugin.

8. CONCLUSIONS

The increasing role of information processing systems in the field cultural heritage allowed to join different knowledge around the theme of digital reconstruction and its communication.
Two levels of interest of this approach, also highlighted within the present research, emerge. They can be summarized as:
- the availability of visualizations and prefigurations that offer scholars the possibility of evaluating alternative hypotheses of philological reconstruction;
- the offer of tools that facilitate communication and interaction with the public, conveying content and proposing narratives in a new way.

The rapid and increasing availability of low-cost technologies and devices, and the simplicity of creating apps and web-apps facilitates the individual fruition of the heritage inside the museum building and remotely, meeting the needs imposed by the continuing pandemic emergency and representing, in any case, an alternative opportunity to the use of traditional devices such as audio guides.

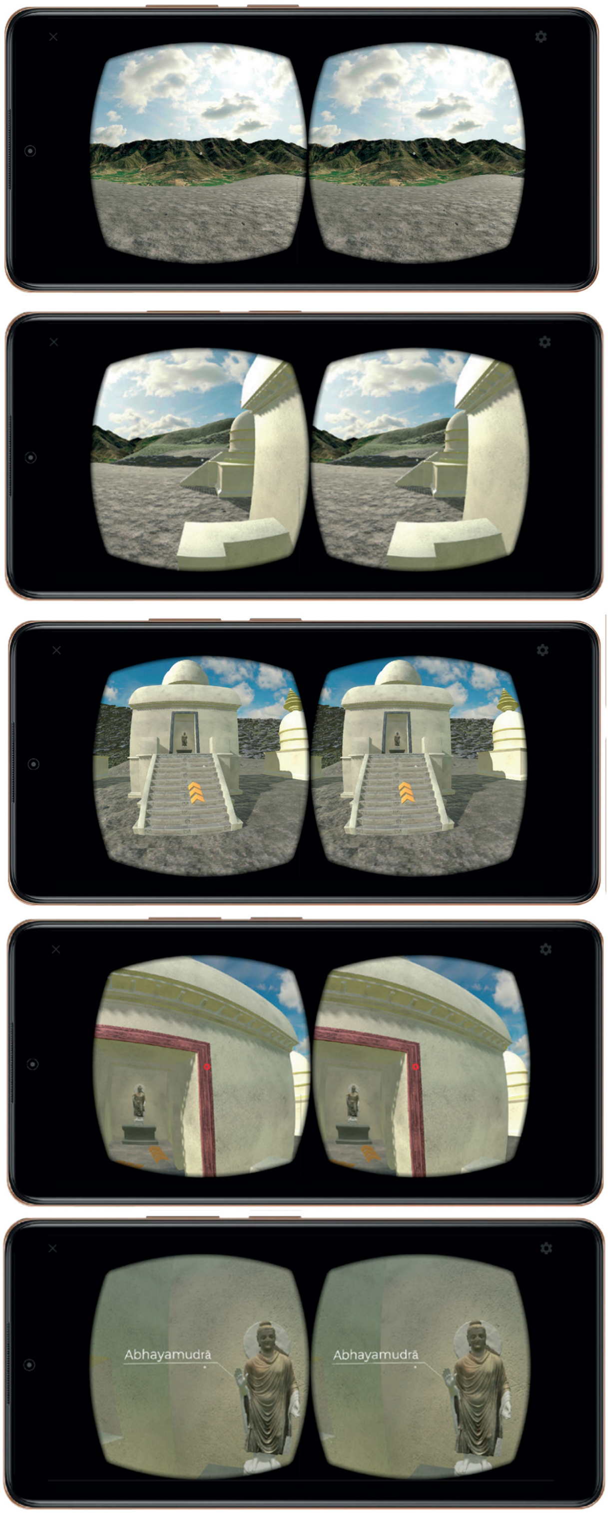

Figure 16. Steps of VR experience.

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Images credits: Figs. 1, 2 photos by F. Ronco; Figs. 3, 4 photos by E. Loliva, Italian Archaeological Mission/ACT; Figs. 5, 6 drawings by F. Martore, Italian Archaeological Mission/ACT; Figs. 7, 8, 9, 10, 11, 12, 13, 14, 15,16 editing by L. Castagna.

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