

Virtual Reality for Spatial Research in Archaeology: Prototyping 3D Reconstruction Tools for the Site of Yeha, Ethiopia

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Abstract: There has been an abundance of research in recent years focusing on the potential of 3D reconstruction and visualisation technologies in cultural heritage and related fields. While many of these are focused on knowledge dissemination with a non-specialist audience, often within the context of museums or heritage sites, fewer studies have dedicated themselves to investigating how such technologies, including Virtual Reality, can be used as tools within the research process. While 3D virtual reconstruction technologies are often implemented by specialists of these technologies in consultation with the heritage researchers themselves, rarely are heritage researchers directly involved in the process of 3D modelling and visualisation. This article describes the development of a real-time 3D reconstruction toolset operated using a VR headset and motion controllers, in this case the HTC Vive. The case study used to test this tool is the archaeological site of Yeha, a town in the northern Tigray region of Ethiopia and the location of an archaeological site with monumental remains dating back to around 700 BCE. This site was chosen as archaeological excavations are currently under way and good 3D scanned data already exists. The 3D reconstruction tool allows archaeologists and other specialists to collaborate within VR to build a 3D visualisation of the ancient site that is able to be adapted as new information is brought to light.

1 Introduction

3D virtual reconstruction is a powerful tool for both research and communication of cultural heritage. Advances in VR, AR, and web technologies over the past decade have allowed virtual 3D reconstructions to become increasingly widespread not only in the entertainment and tourism industries, but also in heritage research communities. In particular, there have been many fine examples of VR and AR incorporating 3D virtual reconstructions used for the communication of cultural heritage sites to non-specialists in the context of museums and visitors' centres.

There has been less research dedicated to exploring how 3D virtual reconstructions can be used in the research process itself, in particular to facilitate collaboration between specialists. A few examples of this are noted in the following section. In addition, within spatial disciplines such as archaeology, there is great potential for developing virtual reality tools that allow different specialists to construct simple 3D visualisations in a virtual environment themselves based on ongoing data collection.

In order to develop and test this tool, the site of Yeha, Ethiopia was chosen as it is an archaeological site currently under excavation within an Ethiopian-German cooperation project between the Authority for Research and Conservation of Cultural Heritage (ARCCCH), the Tigray Culture and

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Tourism Bureau (TCTB) and the German Archaeological Institute (DAI) and for which good remote sensing data already exists. In addition, a number of the research questions related to this project could benefit from a visual reconstruction of the prehistoric buildings at the site. As the excavations are still under way, this visualisation must however be able to evolve in line with the research.

2 Related Work

3D reconstruction, in particular coupled with Virtual Reality (VR), is being increasingly integrated into research and design processes in multiple industries. In the areas of architecture, urban planning and industrial design, commercial-grade tools such as Gravity Sketch have been available since 2014 (GRAVITY SKETCH 2022). In the areas of archaeological and heritage research, experimentation with 3D interactive tools goes back before the advent of commercially-available VR: REUTER et al. (2010) for example have described the development of a Tangible User Interface (TUI), called ArcheoTUI, that helps with the virtual reassembly of 3D-scanned archaeological artefacts. FORTE & WEBB CRAWFORD (2010) furthermore describes the development of a set of virtual, web-based collaborative 3D environments to be used for the purposes of archaeological research and education, based at the University of California Merced.

With the advent of commercially-available VR, some work has been done to integrate it into archaeological research (CASSIDY et al. 2019; TARI 2019). More recently, a joint project between BİMTAŞ, a company of the Greater Municipality of Istanbul, Turkey and the Photogrammetry & Laser Scanning Lab of the HafenCity University Hamburg, Germany, focusing on the 3D virtual reconstruction of the Selimiye Mosque in Edirne, Turkey, provided the opportunity to test VR as a platform for collaboration between specialists for architectural 3D modelling of monuments from the two countries (KERSTEN et al. 2017). A further collaboration between these two partners focused on the 3D laser scanning and virtual reality visualisation of the Rumeli Hisarı, an Ottoman fortress at the Bosphorus in Istanbul (TSCHIRSCHWITZ et al. 2019). In addition, VR has been explored as a tool for architectural historians and archaeologists for preserving a 3D digital copy of the Imperial Cathedral at Königsplatz, Germany that can be explored with a headset and compared directly with the real-world environment through the integration of geo-located 360-degree panoramic photographs (WALMSLEY & KERSTEN 2020).

One of the most successful applications of VR in cultural heritage has been its use as an immersive and interactive tool for knowledge dissemination to non-specialist audiences, often in the contexts of museums. In this regard there are numerous successful use cases. BÜYÜKSALIH et al. (2020) describe for example the workflow for the production of a scanned 3D virtual environment of the İnceğiz caves, in the Çatalca district of Istanbul, Turkey, built in the Unity game engine and for use with the HTC Vive Pro headset. Further recent examples include the reconstruction of the town of Stade, Germany in the year 1620 for exhibition in the Schwedenspeicher Museum, Stade (WALMSLEY & KERSTEN 2019), or the reconstruction of Batavia (corresponding to the modern city of Jakarta), Indonesia in the year 1627 for the Westfries Museum, Netherlands (WESTFRIES MUSEUM 2022).

3 Yeha: the centre of the Ethio-Sabaeen community of Di'amat

An Ethiopian-German team has been undertaking collaborative research at the site of Yeha (Fig. 1) in order to investigate the phenomenon of the migration of southern Arabian populations to the Horn of Africa during the early first millennium BCE (GERLACH 2013; GERLACH 2014a; GERLACH 2017). It is around this time that culture-specific southern Arabian remains of Sabaeen influence begin to be found in south-eastern Eritrea and northern Ethiopia, indicating a cultural shift in this region (FATTOVICH 2009; GERLACH 2015; SCHNELLE 2014; SCHNELLE 2021). This influence is present from the ninth century BCE and is visible at numerous sites in the region in contexts relating to political, social, and religious life: the transfer of culture and techniques extended to the form of rule, the written and spoken languages, religion and cult practices, architecture, building techniques as well as artisanal crafts (GERLACH 2017). Through this process a sustained merging of Sabaeen and African elements was established: out of two diverse societies developed a single new culture that now bears the name “Ethio-Sabaeen” and that endured until the mid-first millennium BCE. The political and religious centre of the newly-established community called Di'amat is located at the contemporary site of Yeha in the northern Ethiopian province of Tigray. Around the middle of the first millennium BCE Di'amat ceases to exist. The best-preserved Ethio-Sabaeen building from Yeha is the Great Temple (mid-seventh century BCE) dedicated to the principal Sabaeen god Almaqah. Given the height of the exterior walls, which at some points are preserved up to the lower part of the roof, 14m above ground level, as well as the state of the rest of the surviving structure, the layout of the inner rooms can be reconstructed as a two-story hypostyle hall with cella walls made of wood and stone. The main entrance took the form of a six-column propylaea with a monumental doorway.

Only 200m from the Great Temple is situated the second monumental structure of the town, the Grāt Be'al Gibri. With dimensions of nearly 60 x 50m this palatial complex of at least four stories was the largest wood-stone structure of eastern Africa and southern Arabia during antiquity. According to C14 dating the structure was first built around 800 BCE and thus is at the beginning of a long tradition of wood-stone architecture, which continues today with traditional Ethiopian architecture (SCHNELLE 2014).

Excavations in the Yeha necropolises have been looking at burial types and customs of the first millennium BCE. As of yet, all burials appear to be pit inhumations with two chambers and a tumulus-like superstructure. Due to plundering and the climate-induced poor state of conservation of the bones, it has been impossible to make further statements on the chronological arrangement of the finds (GERLACH 2017).

Excavations of the antique settlement should illuminate more of Yeha's urban structures as well as its different functional areas and provide material to establish a ceramic sequence. Only through settlement excavations will it be possible to grasp and chronologically situate the complex culture of Di'amat, with its indigenous and exogenous influences (GERLACH 2017).

Alongside scientific research activities, other activities currently taking place in Yeha are the restoration of the antique monumental structures, the development of the site for tourists, as well as the building of a local museum (GERLACH 2014b; TIGRAY CULTURE AND TOURISM AGENCY 2019; LEGESE & ALEMSHET 2019).



Fig. 1: Landscape around the settlement of Yeha, Ethiopia. Blue circle shows close-up of archaeological site

4 Methodology

The Great Temple had already been recorded in the autumn of 2009 by a joint team from the HafenCity University Hamburg and the German Archaeological Institute using terrestrial laser scanning and digital photogrammetry (LINDSTAEDT et al. 2011).

Digital Elevation Models (DEMs) at three separate resolutions were used to construct the topography of the site and its surroundings. Shuttle Radar Topography Mission (SRTM) data at a resolution of 30m (1/3 arc-second) was used to construct an area of 10.33km² surrounding the site. In order to use this data, it first had to be downloaded and processed in QGIS in order to extract a suitable region. 10.33km² was chosen as a suitable area through iterative testing as it seemed to be the smallest area of land in which the VR user could not see the horizon and therefore felt immersed in the landscape. It was also large enough to include several of the neighbouring mountains, which provide useful points for orientation within the virtual environment. The DEM was exported from QGIS as a 16-bit PNG at a resolution of 4096px × 4096px and imported into World Creator 2, a 3D landscape creation and texturing program developed by German development company BiteTheBytes GmbH. The principal advantage of using World Creator 2 as a middle step is that it allows for the procedural texturing of the landscape, which can then be imported directly into UE4. For the area immediately surrounding the site, DEMs of two different resolutions were used: a 10cm resolution DEM that included height information for trees, other vegetation, and buildings at the site; and a 50cm resolution DEM that had been cleaned of all this additional information and contained just information about the height of the land beneath (Fig. 2).

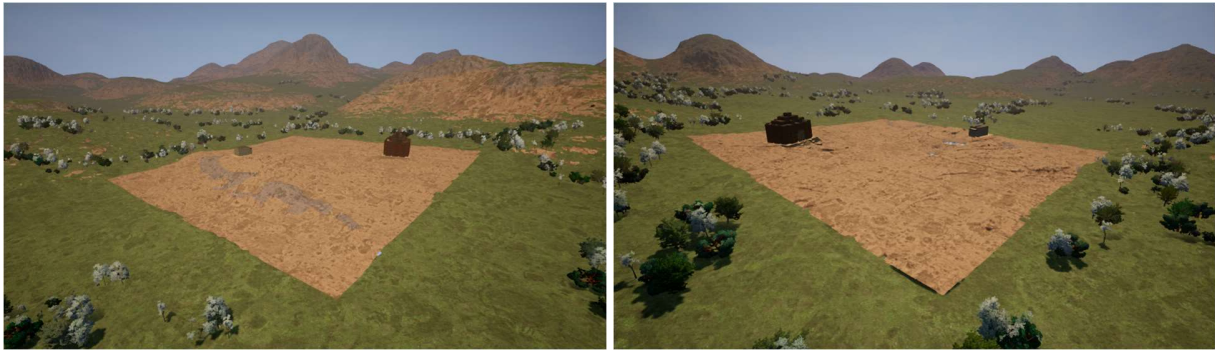


Fig. 2: Multiple-resolution system of landscapes. The background landscape (in green, with trees) is produced from the SRTM 30-meter resolution DEM, the foreground landscape (in brown) from the 50-cm resolution DEM generated by UAV photogrammetry

The area of both these regions was 403.3m². Both DEMs were first loaded into QGIS for data extraction and re-export. The 10cm-resolution DEM was re-exported with dimensions of 4033px × 4033px (1 pixel every 10cm) and imported into UE4 as a landscape object. The origin of the virtual world was taken to be the origin of the UTM zone in which the DEMs were located (UTM 37N). The 10cm-resolution landscape object was then transformed in its x, y and z coordinates to its corresponding point within the UTM zone (this information was extracted from QGIS). In order to calculate the correct z-scale of the landscape, the following formula is provided in the Unreal Engine 4 documentation:

$$z^{\text{scale}} = 100(H^{\text{d}} - H^{\text{l}}) \times 1/512$$

In this formula, H^{d} refers to the altitude (in metres above sea level) of the highest point on the DEM, H^{l} refers to the altitude of the lowest point and z^{scale} refers to the scale factor within UE4. The figure of 1/512 is arrived at due to the fact that the UE4 reads 16-bit png values on a scale between -256 and +256 (512 values total). This allows us to arrive at a z^{scale} value for the 10cm-resolution DEM of 9.3163. The same workflow was also used for the 50cm-resolution DEM. This DEM was exported from QGIS with dimensions of 806.6px × 806.6px (1 pixel every 50cm). The z^{scale} was calculated to be 7.197.

In order to integrate the laser-scan data within the virtual environment, each model was first imported into a 3D program, Blender, and reduced to around 200 thousand polygons using the “Decimate” modifier. The model was then re-exported as an .obj file and imported into UE4. Since an .obj file retains the world position of the object in the vertex data, the origin can be set to the world origin within UE4 and the object then sits at the correct location in the world.

With the DEM-generated landscapes and laser-scanned models now sitting at the correct position within the virtual environment, the landscape object could then be adapted to reflect the historical height of the land, as revealed by the archaeological excavations. Using the native landscaping tools within UE4, the surface of the DEM-generated landscape was adjusted to the height of the laser-scanned models. The area of land in between the models was also adjusted so as to gradually slope from one model to another. In these areas then, the height of the land was extrapolated from the known data points of the laser-scanned models. Finally, the terrain overlaying the 3D model was made transparent in order to allow users to see the model properly (Fig. 3).



Fig. 3: Terrestrial scanning data (grey) of one of the archaeological trenches, integrated within the virtual environment in the lower height level of the past

Once the environment had been set up to accurately visualise the physical environment, a number of tools were programmed to allow users (primarily archaeologists and geophysicists) to create and visualise buildings and other historic and prehistoric structures in the environment according to archaeological data. In collaboration with project partners, a number of functionalities were prototyped and implemented. The following functions were programmed in UE4 using the native Blueprints C++ visual coding tools.

- i. Place new buildings on the terrain and define their dimensions: Pressing the menu button on the VR motion controller twice brings up the building placement menu. A user interface is also created to help the user pass in values for the width, length, height and rotation of the building using a slider. A ray-tracer allows the user to point at a point on the terrain and generate a building at that location when they press the trigger button on the VR motion controller. The numerical values for the different dimensions are also displayed alongside the sliders (Fig. 4)

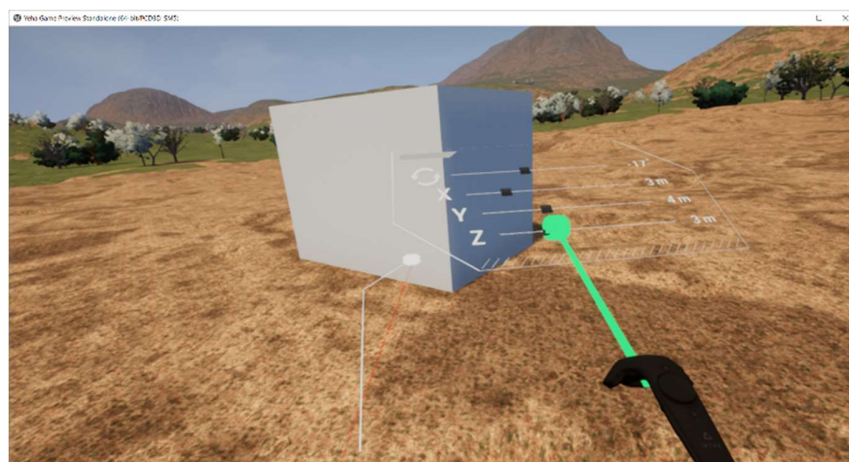


Fig. 4: User interface with sliders for the placement of the new buildings enabling the user to input values for the width, height, length and rotation of the building mesh

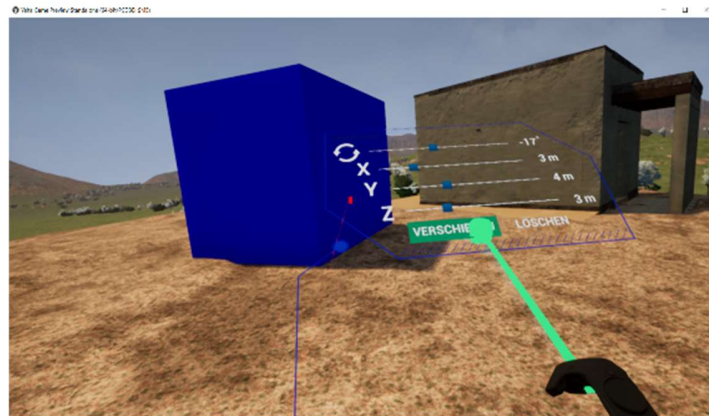


Fig. 5. User interface for editing the building, allowing the user to change the dimension parameters of the mesh, as well as move it to a new location on the terrain or delete it altogether

- ii. Allow the dimensions of these buildings to be edited after they have been placed: Once the building has been placed on the terrain, it can be further edited by pointing the VR motion controller at the mesh and clicking the trigger. This brings up an editing UI with the previously defined width, height, length and rotation displayed on sliders. These sliders can be further moved in order to change these parameters. While a building is being edited, it is highlighted dark blue to distinguish it from other meshes (Fig. 4).
- iii. Allow the building to be moved to a new location on the terrain or else deleted: At the bottom of the editing UI there are options that allow the user to delete the building (the building mesh is therefore removed permanently from the world) or move it to a new location. In order to perform this latter operation, the user must then point to a new location on the terrain and once again click the trigger button of the VR motion controller in order to place the building at its new location (Fig. 5).
- iv. Save the location of the buildings before closing the application and load it when starting again: If the environment contains buildings that the user would like to save before closing the app, the 'S' key on the keyboard allows them to save the environment in its current state. This state will be automatically loaded when the app is restarted. In order to delete the state, the 'D' key can be pressed during play, and the current state will be cleared from the cache (Fig. 6).



Fig. 6: Messages notifying the user that the data has been saved (left) and/or deleted (right)

- v. For the Almaqah Temple and Grat Be'al Gibri (Fig. 7), users should be able to view the different building phases: By pointing the VR motion controller at one of these buildings and clicking, the user is able to bring up the phase UI. This contains a menu allowing the user to replace the visible mesh with a mesh representing another phase in the building's life (Fig. 8). In this way the different phases can be directly compared within the same virtual environment.



Fig. 7: Reconstructed buildings in Yeha - Grat Be'al Gibri (left) and Almaqah Temple (right)

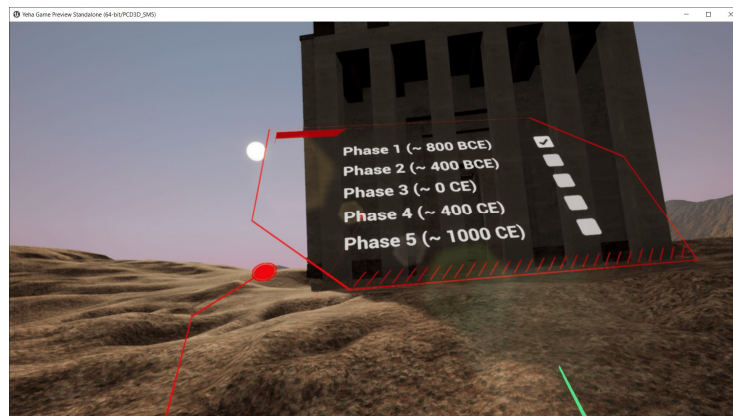


Fig. 8: Menu for selecting different building phases of the Almaqah temple by pointing the VR motion controller

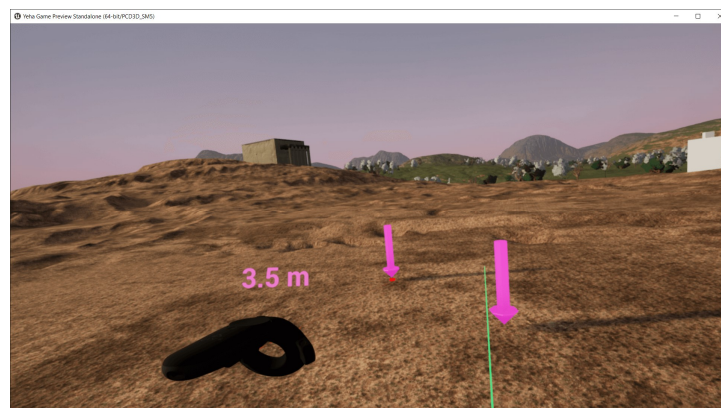


Fig. 9: Measurement tool, which consists of two anchor points placed on the terrain and the numerical value for the distance between them, displayed above the left controller

- vi. Measure the straight-line distance between two points on the terrain: Pressing the menu button on the VR controller once brings up the measurement interface (Fig. 9). Again, a ray tracer allows the user to target a location on the terrain to place the anchor point for the measurement. Clicking the trigger button once places this anchor point at the location and activate a second arrow to which the distance is calculated. The distance in metres appears as a numerical value above the left motion controller.

One function that had been envisaged but was not able to be implemented was one allowing the user to import new 3D models from a local or remote drive and integrate them into the virtual environment during play. This was deemed not to be possible due to restrictions on the way in which developers are able to use the Unreal Engine, which seems not to support real-time import of 3D models due to concerns surrounding software stability and security.



Fig. 10: The reconstructed archaeological site of Yeha with the Grat Be'al Gibri in the background and Almaqah Temple in the front indicating the present buildings in grey.

5 Conclusion and outlook

The VR reconstruction tool and associated functions for real-time 3D visualisation provide a starting point for the further development of VR tools for archaeological and architectural research. Further tests are already being conducted with data from another related site, that of Sirwah in Yemen, where there is a temple belonging to the same tradition as at Yeha. While there is a significant body of work dedicated to using VR in cultural heritage, much of this has focused on VR as a tool for knowledge dissemination, rather than as one for the research process itself. This paper addresses this gap and describes a number of prototyped tools that can be used by

archaeologists and other specialists themselves to visualise a site in real time. Further research might include tools to change the resolution of the landscape (for example by swapping out a low-resolution terrain for a high-resolution one), load in new 3D models in real time, and more detailed modelling tools for different kinds of structures. Finally, the archaeological site of Yeha has been reconstructed in virtual reality including the landscape of the environment, the two ancient buildings Grāt Be'al Gibri and Almaqah Temple, and the present buildings indicated as boxes in grey (Fig. 10).

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