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Experiments with Mixed and Augmented Reality (MR/AR) for Archaeological Data Collection and Use During Fieldwork: Vision for the Future

RESEARCH ARTICLE

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ABSTRACT

Most prior uses of mixed and augmented reality (MR/AR) in archaeology have focused on tourism, museums, and education, but we see bright potential for using 3D immersive technologies directly during active excavations. As a first step towards this vision, we ran four experiments with three different head-mounted hardware devices during our fieldwork in the South Caucasus. The devices are the Vuzix Blade 2 AR smart glasses, as well as the Microsoft HoloLens 2 and Meta Quest Pro MR headsets. Our first experiment aims to replace our smartphone data collection workflows with the hands-free AR and MR headsets using gesture interaction and voice recognition. Our second experiment used MR to allow us to view precisely placed 3D models of previously excavated remains in situ in the trench for stratigraphic comparisons. Our third experiment implemented a novel depth-guidance system in the HoloLens 2 to guide real excavation towards a precisely flat surface. In our fourth experiment, a user wearing the HoloLens 2 joined real and virtual pottery sherds in the excavation lab. Although the currently available hardware devices are not yet sufficient for regular use during fieldwork, our experiments demonstrate significant potential. Therefore, we plan to continue building towards our vision for the future where MR and AR immersive technologies provide enhanced vision and data interaction to working archaeologists in the field.

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1. INTRODUCTION

Within our field of archaeology until now, almost all uses of mixed and augmented reality (MR/AR) have focused on applications that present the past, usually in the context of tourism, museums, or education (Bekele et al. 2018; Efkleidou et al. 2022; Hammady et al. 2020; Vlahakis et al. 2001). This makes a lot of sense, since these are ideal technologies for visually combining the naturally three-dimensional (3D) information of archaeology with the real world we study, in a manner that is highly intuitive for the public. These technologies remove abstraction layers that otherwise try to describe what the past looked like, instead just showing it as we think it looked. The best experiences, provided by head-mounted MR devices, immerse users and support spatial thinking through a fully embodied experiential interaction between the virtual past and its real remains (Cobb et al. 2024a). Moving beyond just presenting the past, a few selected studies, as outlined in Liang (2021) and discussed below, do find interesting applications for MR/AR in actually supporting primary archaeological research. We see a future where we as archaeologists use AR/MR vision as part of our daily archaeological fieldwork, where the digital augmentation of our 3D visual reality will become as essential and common an archaeological tool as the trowel. To set the stage and begin thinking about that future, our team experimented with the current state-of-the-art in MR/AR headsets during actual fieldwork. We used the devices at an excavation trench as we dug and we began developing ideas about how, once the hardware is ready, any archaeologist could benefit from MR/AR in the collection of and interaction with primary archaeological data.

Our primary focus here is on the practical aspects of both what is currently possible as well as envisioning the future possibilities of how MR/AR could enhance day-to-day fieldwork. It is crucial for our community to share results from such careful testing of hardware and to share innovative ideas so that we can each build on each other's work. This type of work on new computer applications in archaeology requires significant investment in time and effort, so we can avoid duplicating the work of others by sharing results publicly. We accept that existing MR/AR headset hardware is not yet sufficient for daily use at an archaeological field project, but with the promise of more devices coming in the next few years, we believe this is the time to set the groundwork for the exceptional potentials this technology may one day present. As with the introduction of any new technology into archaeological practice, our community will eventually need to examine the impacts on how and why we do our work, and on our ways of thinking, within existing critical theoretical contexts (Caraher 2016; Morgan & Wright 2018; Waagen 2019). For example, our experiments highlight the potential of being able to view, on demand and in the trench, the spatial and visual information about things that have already been excavated. This would no doubt influence interpretations and the decision-making processes of where and how to dig next, with all the inherent implications. Of course, we are still very early in these stages of MR/AR use directly for archaeological data collection and analysis. The first step, therefore, is to know what is possible and to set plans for future implementations, the contribution we strive for here. As Rowe (2019:59) stated in a thesis about AR in archaeology: "The possibilities are vast, and it all starts with a knowledge of what's been done and some imagination of what could be done."

In this paper, we document the results of four experiments we ran at our field project in Armenia during the summer of 2023 using three different hardware devices. We focus specifically on wearable head-mounted devices because archaeologists require both a fully immersive 3D experience and hands-free interaction with data, to prevent interruptions with the manual work and tactile research. We follow Liang (2021) in her definitions for MR and AR that see both technologies along a spectrum between full reality and the closed, entirely computer-generated environments of virtual reality (VR). AR provides simpler, informational overlays to the real world, usually with a smartphone, whereas MR provides an immersive experience closer to VR, where a head-mounted device places 3D graphics directly within the user's view of the real world. Specifically, we tested the Vuzix Blade 2 smart glasses as an AR device and the Microsoft HoloLens 2 and Meta Quest Pro as MR devices. Our four experiments include (1) replacing our smartphones for basic data collection, including database entry, 2D photography, and narrative journaling, (2) interacting with previously excavated 3D archaeological contexts within the space of the real trench, (3) guiding precise digging with MR spatial awareness, and (4) combining and comparing real and virtual artifacts during field lab research. We share what we learned to encourage other experiments and to explore the possibilities for future vision in data collection and use during archaeological fieldwork.

2. PRIOR WORK WITH MR/AR IN ARCHAEOLOGY

The largest and most detailed dataset at many field projects is or will soon become the accumulation of 3D spatial and morphological data. Archaeologists collect 3D data to describe excavation contexts and to map landscapes, and can also scan ceramics and other objects. As data acquisition becomes easier, the challenge shifts to interacting with and analyzing these abundant 3D models. We remain limited in our ability to interact with this information because our current digital interfaces are mostly two-dimensional screens. Our primary spatial analysis tool, Geographic Information Systems (GIS), was also only designed for two-dimensional processing. The 2010s saw the emergence of several types of affordable and high-quality immersive technologies that enable visual interaction in three dimensions (Stein 2019). Particularly important to archaeology has been and will be the development of MR and AR. One hopes that head-mounted MR can also enable easier creation and editing of 3D models than we can do today through our 2D screens (Holmes 2019).

MR and AR have, until now, mostly been used for public engagement and education in archaeology (Bekele & Champion 2019; De Bonis, Nguyen, & Bourdot 2022; Gaugne et al. 2022; Innocente et al. 2023). For example, MR can enable a group of students to virtually tour a remote archaeological site together within their own classroom, seeing each other as well as the 3D models of buildings and landscapes. AR has been used to teach about virtual objects within the real world (Pollalis et al. 2018). At archaeological sites, experiments have guided tourists with spatially aware MR/AR devices (Bekele 2019; Muñoz & Martí 2020; Pierdicca et al. 2016). These tours may have virtual anthropomorphic guides or virtual actors simulating ancient people in the ancient streets (Papaefthymiou et al. 2017). The user could view virtual reconstructions over the remains of actual building foundations, with the ability to compare multiple possible interpretations (Dragoni et al. 2019). This type of interaction is already popular with smartphone and tablet-based AR, even in underwater archaeology (Bruno et al. 2019). Once head-mounted devices become more comfortable, affordable, and effective, we can anticipate their broader use for public engagement too. Crucially, the visitor experiences all of this within the actual landscape and environmental context of the real site.

Moving beyond just presenting information and telling stories, MR has multiple potential uses to support primary archaeological research. For example, a HoloLens has already been used to manipulate and annotate 3D models of sections of cave art (Barbier et al. 2017). Furthermore, MR and AR could be used as tools to directly support archaeological excavation, whether on or off a real site (Fogliaroni 2018:18). With the help of medical imaging technology, Gaugne et al. (2019) created 3D scans to map the locations of bones and other objects in a burial urn. Using MR to look ‘inside’ this urn through graphical projection, this technique assisted with the urn’s actual micro-excavation (Gaugne et al. 2022). MR has also been used to train students in manual techniques. The project of Brondi et al. (2016) focused on teaching intangible heritage by having students mimic the movements of virtual hands over their own real visible hands with the HoloLens. This allowed the students to attain the muscle memory for creating printmaking stamps or weaving on a loom.

In several domains outside of archaeology, such as construction, agriculture, and infrastructure maintenance, people have also been experimenting with deploying MR/AR directly in fieldwork (Caria et al. 2019; Salman & Ahmad 2023; Savini et al. 2023). Within archaeology, there have been few immersive attempts to use the technology on-site during fieldwork. Dilena and Soressi (2020) developed a tablet app that uses AR to replace artifacts in situ at a paleolithic site in France. This can help users to interact with specific finds in their original locations, including zooming in and out and seeing object orientation relative to other objects and the landscape. Furthermore, as part of their proposal for a comprehensive data collection and analysis app for their fieldwork, Psarros et al. (2022) briefly mention developing some basic data collection functionality for the HoloLens. Our study turns the focus to actually deploying head-mounted, fully immersive technologies in the field for data collection and use, directly during an active excavation. By putting the current technology through its paces, we can get a better understanding of what is possible now and develop a vision for the future potential of these technologies on the site.

3. THE TECHNOLOGY FOR THE EXPERIMENTS

We sought to use a diverse set of hardware products during our fieldwork, so we selected devices based on availability and relevant features. Through the generous support of our university’s Libraries and our Faculty of Engineering’s Innovation Wing, we were able to acquire three devices, so cost was less of an issue. First, we wanted to test a straightforward and comfortable pair of smart glasses for basic data work. A cursory internet search led us to the Vuzix company and their Blade 2 product, which costs USD 1300 (Figure 1; https://www.vuzix.com/products/vuzix-blade-2-smart-glasses). These are essentially a thick pair of eyeglasses, with a small transparent screen projected onto the lens of the right eye – you see the digital screen with only one eye and you see the real world through it. The screen can display color 2D graphics with a total area resolution of 480 × 480 pixels. A forward-facing camera for capturing images and video is located above and to the left of the left eye. The user can navigate in the screen using voice commands or using a touchpad located along the right edge of the glasses, by swiping and tapping with a finger. This cordless, self-contained device also has Wi-Fi and Bluetooth connectivity. Although by default the lenses are simply transparent with UV-protection, you can purchase special prescription lenses to replace your normal glasses, since it is hard to wear both at the same time.

Figure 1 Left-to-right: Vuzix Blade 2, Microsoft HoloLens 2, Meta Quest Pro.

The Microsoft HoloLens 2 has been the main MR headset available on the market for several years, with a cost of USD 3500 (Figure 1; https://www.microsoft.com/en-us/hololens/). This is a cordless, head-mounted device with built-in computer and battery, and 64 GB of storage. The HoloLens 2 has local spatial awareness that scans your surroundings and then projects digital graphics onto transparent screens in front of each eye, using parallax to present a 3D view. This allows for an effortless and seamless experience of seeing virtual objects as if they are actually in your real world, such as sitting on a real table or hanging on a real wall. The external sensors also support gesture recognition, where the user's hands are tracked by the hardware to become a means to interact with the digital environment. The HoloLens 2 is relatively heavy, but since your face is not covered, some find it more comfortable to wear than closed VR headsets. Among the limitations discussed below, a main problem is the limited field of view into which graphics can be projected, as the screens provide only a rectangular area that diagonally measures 52 degrees. Although the HoloLens 2 version was released back in 2019, it is uncertain whether Microsoft will continue development of this product for an eventual third version.

Finally, the Meta Quest Pro is actually a VR headset which costs USD 1000, but it enables MR functionality by 'passing-through' a live color video feed from its external forward-facing cameras (Figure 1; https://www.meta.com/quest/quest-pro/). Although the cheaper (USD 300) Meta Quest 2 VR headset also enables pass-through, that device only displays live black and white images. The Quest Pro can superimpose graphics onto the color pass-through in each eye, which makes the virtual objects appear as if they are in the full 3D real-world through parallax, and it has 256 GB of local storage. This device has a 120-degree diagonal field of view, over twice that of the HoloLens 2, but the closed environment does not cover full human vision, so the user loses some peripheral vision in VR and MR modes, giving a slight tunnel-vision effect. The Quest Pro has minimal spatial awareness of its surroundings, only enough to keep objects locked into place in the real world. But, it does enable gesture interactions by tracking the user's hands, as well as voice interaction through Meta's Voice Software Development Kit (SDK). Since it is a VR device, it also must establish a 'working boundary,' called a Guardian, which is an area of the real world within which the user is contained for safety and because of processor limitations. For VR, if the user wanders outside the Guardian boundary, they may run into a wall or furniture which they cannot see, so the device warns them by showing a virtual grid edge of the boundary and opening the pass-through view. Although a boundary is pointless for MR, the boundary still exists in the Quest Pro and, since the device's boundary has a real-world size limit, it unfortunately also limits the area within which MR can be used. The Quest Pro is bulkier than the HoloLens 2 since it encloses the face, which some find more uncomfortable for long periods of use.

In addition to selecting hardware, we also needed to create our own software to support each of our experiments with the three devices. Each device runs a different operating system, with the Blade 2 and the Quest Pro relying on very different customized versions of Android, while the HoloLens 2 runs a special version of Microsoft Windows. Thus, not only did we need to develop our own custom software, but we also had to support it on very different base technologies. A computer science undergraduate developed rapid-prototype apps for each of the systems using the Unity C# programming language, relying on a variety of different programming frameworks and libraries for the different devices. Specifically, he used the Microsoft Mixed Reality Tool Kit 2 (version 2.8.3.0) and the Oculus Integration package (version 55.0). The HoloLens 2 also has an official Emulator that can run on Windows machines and enables testing of apps before they are loaded on the device. To deploy a Quest Pro app, we exported an Android Application Package (APK) from Unity, and sideloaded it onto the headset. For the HoloLens 2, a Universal Windows Platform file was exported and compiled into an .appx file through Microsoft Visual Studio, which was then deployed to the HoloLens 2 through its device portal (Rahaman, Champion, & Bekele 2019). Our programmer also learned about archaeology and how to work with digital 3D data and spaces (Anderson, Adzhiev, & Fryazinov 2021).

Finally, in order to share our findings here, we needed ways to capture screenshots or internal video, a view of what the user sees at any given time, including the computer-generated content against the real-world background. This was easiest on the HoloLens 2 which natively supports this functionality. The Blade 2 claims to have a way to capture what is visible on its tiny screen, without the real-world backdrop, but this function does not work yet. The Quest Pro has some privacy settings that prevented building functionality into our own app to capture the user's view of digital 3D models with the live pass-through background. By default, the in-app screen capture would only record the digital 3D models against a black background. However, a native Quest app can be opened separately to capture the combined digital and live view which the user sees in our app, but we could only retrieve those image files through a wired connection. For all devices, we also captured some photographs by simply placing a smartphone camera behind the glasses. These images are invariably imperfect since the screens are designed for the human eyes.

4. OUR ARCHAEOLOGICAL CONTEXT

We conducted our experiments as part of the summer 2023 field season of an active archaeological project, the Ararat Plain Southeast Archaeological Project (APSAP). Along with 2022, this was the second full field season of APSAP, which is a collaboration between the University of Hong Kong and the Institute of Archaeology and Ethnography of the Republic of Armenia's National Academy of Sciences. Our field project investigates the Vedi River valley of Armenia, aiming to better understand past life and mobility within mountain-plain intersections (Cobb et al. 2024b). The valley has always been an important transportation route, connecting the agricultural Ararat Plain to the west with the resource-rich mountain ranges to the east. We have conducted field survey to locate areas of past human activity throughout the valley and are excavating its main site, the Vedi Fortress, which holds a commanding view over the valley's entrance. The site was first fortified with lower and upper lines of monumental fortification walls during the Late Bronze Age (ca 1550 BCE) until it was likely destroyed at the end of the Iron Age 1 Period (ca 800 BCE). After that, the walls were reused during the Sasanian Persian Early Medieval Period (Late Antique; ca 450–650 CE). This field project and its predecessors have served as laboratories for experimenting with digital technologies in archaeological fieldwork (Cobb, Earley-Spadoni, & Dames 2019; Wang et al. 2021).

5. THE EXPERIMENTS

Our experiments were designed to test what is currently possible with the available MR/AR headsets. We also present some ideas about the future potential affordances of using these technologies to support and enhance our archaeological fieldwork and research. Table 1 provides a quick view of the four experiments, which are described in detail in the following subsections.

5.1. EXPERIMENT 1: AR SMART GLASSES AND MR FOR TRENCH DATA COLLECTION

Our first experiment was also our simplest: We wanted to see if AR smart glasses could serve as the primary platform for basic hands-free data entry during excavation, incorporating database entry, 2D photography, and continuous narrative journaling. The goal is to replace the smartphones we use for collecting these types of data, our main data, at the trench. We primarily focused on testing the Vuzix Blade 2 device during this experiment, but we also ran some basic tests for journaling with the other two MR devices. We began by trying to use our existing custom smartphone

EXPERIMENT	AIMS	HARDWARE	SOFTWARE DEVELOPED
1: AR smart glasses and MR for trench data collection	Replace smartphone-based data entry with heads-up, hands-free entry, including for database work, 2D photography, and narrative journaling	Primarily the Vuzix Blade 2; Journaling experimentation also with the Microsoft HoloLens 2 and Meta Quest Pro	Testing of existing software; New interface for database entry including 2D photography, based on our existing custom smartphone app; Improved voice-recognition software for text entry
2: MR for reviewing 3D context models in situ	Place previously removed 3D information back into the trench to support decision-making and interpretation through the visual analysis of spatial relationships	Microsoft HoloLens 2 and Meta Quest Pro	Workflow for precisely geolocating selected 3D context models into the trench; Ability to further manipulate their sizes and positions
3: The potential for MR-guided excavation	Demonstrate the potential that MR can be a tool used during actual excavation; Test a workflow for guiding excavators to dig flat surfaces as needed	Microsoft HoloLens 2	Interface, controlled by hand-gestures, for placing a virtual plane into the real space, which appears once the user uncovers to the specified depth
4: MR for artifact analysis	The ability to carefully manipulate virtual artifacts, including to compare them with real object shapes and to reconstruct pottery vessels and other types of objects	Microsoft HoloLens 2	Importation of selected 3D artifact models and the ability to manipulate these with hand gestures

Table 1 Summary of the aims of the four experiments, which hardware devices were tested, and a description of the custom software developed to support each experiment.

database app and the Evernote app on the Blade 2, but we have since rebuilt our custom app for the Blade 2's interface. Through these initial experiments, we have learned about the possibilities of the hardware, as well as about the challenges that we still need to overcome during future development and testing.

We currently depend on Android smartphones for fundamental data collection at the trench, using a custom app to record basic information about our distinct excavation contexts, to photograph the contexts and find bags, and to keep a running freeform daily journal in Evernote. We additionally collect 3D photogrammetric data with dedicated cameras and differential global navigation satellite systems (dGNSS) equipment, given the deficiencies of smartphones, but that type of data was not a focus of this experiment. We have run into some challenges with using smartphones during excavation. For example, excavators must pause digging to remove the phone from their pocket to work in the database or add to the journal, so work is interrupted and journal writing happens less often than it should. For convenience, the phone is sometimes left out on the ground, where it may be covered with dust, potentially blocking or even scratching the camera, and there is always a chance someone could step on the phone. Smart glasses could both enable hands-free data entry and review, while at the same time providing some protection for the eyes from dust and the sun (Vainstein, Kuflik, & Lanir 2016). Thus, we took the Vuzix Blade 2 to the trench over the course of several days, trying the device when the sun was low in the early mornings as well as during the bright mid-day sunlight (Figure 2; Figure 3). The Blade 2 connected to the internet using mobile hotspots from our smartphones at the local 4G speeds.

First, we attempted to install our existing custom smartphone app, which allows database entry and photography, onto the Blade 2. This device runs the older Android version 11, compared to our phones running version 12 or 13. Although the app loaded, the small screen has many limitations, and performance and interaction were especially challenging (Figure 4). The app expects touch screen interaction, but the Blade 2 can only either scroll among input boxes or use a mouse-cursor, and typing characters is cumbersome. The Blade 2's build-in functionality for a mouse-cursor was laggy and crashed. Although we found that the original smartphone version of our custom app was practically unusable, it is a relatively simple client that mostly relies on remote web service calls to our central server. Thus, after the summer, our programmer has been iteratively updating and testing a new version of this custom database app designed specifically for the Blade 2. The main change has been the simplification of the user interface, which now first presents only a selection of the trenches. The user scrolls through these options using the right finger, finally clicking to select a trench. The next screen then provides the ability to either create a new context in that trench or choose from existing contexts, with the latest ones displayed initially on the screen, and the rest accessible by scrolling down. Once a context is selected, the next screen allows the user to update database information such as date opened or closed, context type, or a short text description. We have had some success training a Large Language Model (LLM) to support voice-recognition for adding and updating these textual descriptions. Finally, a user can take 2D photographs of the context or its find bags in the field, and these are uploaded to our server. We are in the testing phase for this new app, continuously improving the user experience and stability, with plans to try this in the field during a future season.

Figure 2 Using the Blade 2 during excavation.

Figure 3 Photograph through the Blade 2's right lens showing its tiny home screen.

Figure 4 View of our custom app's login screen in the Blade 2.

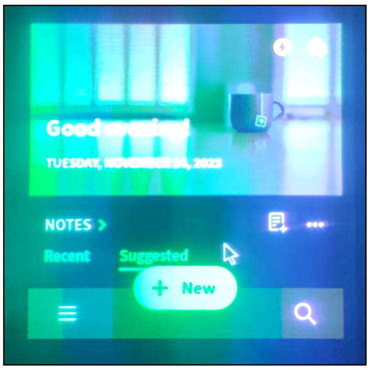


Figure 5 View of Evernote in the Blade 2, with local mouse pointer.

We also tried to install the Evernote app on the Blade 2, but again found it barely functional for two basic types of data entry (Figure 5). First, we purchased a license for Vuzix's speech-to-text (STT) program, and we were able to speak some small narrative as text entry, though it was not accurate enough for regular use. As mentioned before, we have since developed greatly-improved LLM-supported voice-recognition, but we will need to find a way to integrate this with Evernote. Second, since the Blade 2 can capture forward-facing video and still images with its 8-megapixel camera, we were able to load a photograph into Evernote. The built-in voice activation functionality also worked well for basic navigation and operating the camera, by simply saying 'Vuzix, take a picture.' Although it does occupy the right hand, scrolling with the right finger did function well and is still quicker and easier than taking the phone out of a pocket, but we need further experimentation when wearing work-gloves. We are considering to create our own custom journaling software in the future to replace Evernote to better fit this platform.

In terms of being able to use the Vuzix Blade 2 on a regular basis, our experience indicates that this form factor would work very well for use throughout the excavation day at the trench. The device is comfortable, has good internet connectivity, a decent camera, and interaction via voice or finger is sufficient. Perhaps the main downside at the moment is the screen, but our latest software is specifically designed for its limited size and interactivity. We may also find that looking through the screen with only the right eye could become uncomfortable after long periods of use, though most of the time the screen could remain off and, although we have not fully tested battery life, it appears to last all day. Sunlight was a challenge for the Blade 2, but less than for the HoloLens 2, so the Blade 2's screen could still be brighter. It helps to look at a dark background to see the screen. We are also working on two directions to improve this situation. First, we purchased add-on sunglasses-type shades that are placed on the exterior of the lenses. Initial testing indicates that this decreases the contrast between the real-world and the screen by decreasing overall brightness. Second, we are also planning to experiment with other types of smart glasses that have an actual non-transparent screen placed in the peripheral vision of the user, including by building our own smart glasses from parts.

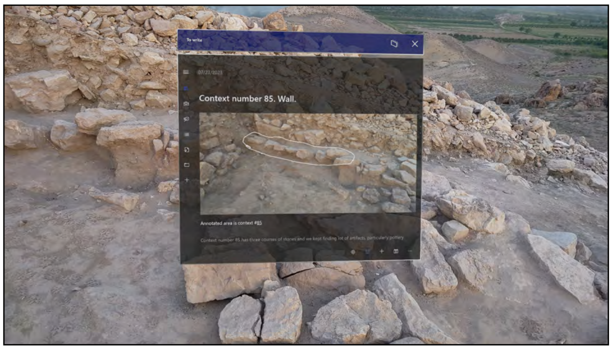
Separately, we envision great potential for the use of such AR smart glasses for field-walkers during archaeological surface survey. Although less crucial to have hands-free data entry, there are times in our region when we find ourselves scrambling over difficult terrain with our hands. The Blade 2's built-in camera, if paired with a global navigation satellite system (GNSS) position from a connected device, could support a smooth data collection workflow. Furthermore, the heads-up display could show a map with the walker's real-time position, including marking the track already walked and helping keep team members within their designated sampling lines. In addition, with local wireless connectivity, the map could show the positions of other walkers to improve team coordination, and could even perhaps show an initial distribution of find locations made by the team.

Since our two MR devices have more capabilities than the Blade 2, we briefly experimented with using them for the same type of basic data collection within the trench. Although it would be less practical to wear the HoloLens 2 while excavating all day, we were able to successfully replicate some of our smartphone functionality. Specifically, we found third-party note-taking applications for the HoloLens 2 that used voice recognition and image capture (Figure 6; Figure 7). These functioned moderately well, but the voice recognition was not accurate enough for regular use. We also built our own custom software workflow to implement basic note-taking functionality within the Quest Pro (Figure 8). We experimented with Google's online speech-to-text service, but this requires uploading an audio file and thus does not fit with our real-time writing needs.

5.2. EXPERIMENT 2: MR FOR REVIEWING 3D CONTEXT MODELS IN SITU

MR has the potential to fill a very important gap in archaeological practice, namely, the ability to see previously excavated remains placed precisely back into their original locations (Dilena & Soressi 2020).

Figure 6 HoloLens note-taking app with voice recognition and keyboard entry, user view inside the headset.



Context number 85. Wall.

Annotated area is context #85

Context number 85 has three courses of stones and we kept finding lot of artifacts, particularly pottery

Figure 7 HoloLens note-taking app with annotated photograph, user view.

2023-07-25-06-29-07: this is essentially a test for the text-to-speech model and we are recording it right now in real time

Figure 8 Quest Pro custom note-taking app, user view.

Figure 9 Using the Quest Pro in the trench to view 3D models in situ.

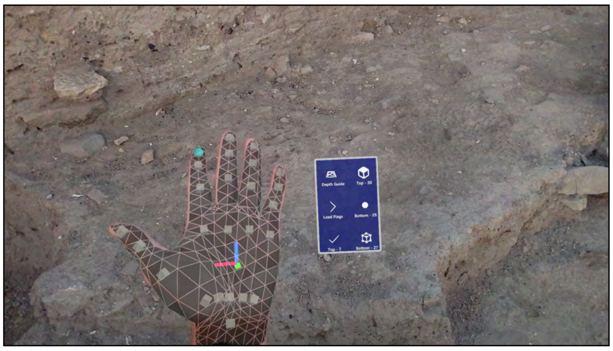


Figure 10 Custom app menu for loading models, HoloLens user view.

This could be for artifacts, both large and small, for architecture and other features, or for any volumetric excavation context. These would aid with understanding stratigraphy, comparing scale, planning how to excavate next, and generally thinking through a wide variety of important archaeological questions (Figure 9). The use of MR at the trench could also open possibilities for group collaboration. Multiple users could view the same 3D models in the same place at the same time, from different angles while still seeing each other, thus encouraging discussions (Sereno et al. 2022). Through today's high-speed internet connectivity, it could even be possible for people not physically present to take part in the field discussions. If excavation projects would start sharing their primary 3D data openly, we could imagine directly comparing walls, features, and spaces among different sites at full 1:1 scale (Cobb and Nieminen 2023:244). Users could also use MR to view geophysics data on the surface to determine where to excavate next.

Thus, for this second experiment, we tested the viewing of 3D models of previously excavated contexts replaced back in situ in the trench. For this experiment, we used the two MR devices that enable such spatially-aware 3D immersion. At our excavation, we capture 3D models using photogrammetry whenever we complete the excavation of a distinct volumetric context (Roosevelt et al. 2015). Our programmer developed custom software with a small selection of our actual 3D models to display in the trench using the HoloLens 2 and the Quest Pro (Figure 10). The user interacts with these apps through intuitive hand gestures to scroll through virtual menus that appear to float before them in the air. An important step in this process was geolocating the models in their proper positions, even though the headsets do not know their location on Earth, so we developed an anchoring solution. We spent several days at the trench investigating what was possible, how things looked, and documenting the current limitations. These initial experiments have enabled us to plan future work that also integrates more closely with our database.

Within the top trench at the Vedi Fortress, the entire 10-meter western edge originally contained an Early Medieval (Late Antique) rebuilding of the site's main upper

Figure 11 User view from inside the HoloLens of the virtual fortification wall.

Figure 13 The user looking at the virtual wall.

Figure 12 Photograph through one HoloLens screen, similar angle, colors result from fast camera shutter speed.

Figure 14 Closer view of the wall from the Quest Pro, user view.

Figure 15 HoloLens user view of the storage vessel (left) and adjoining wall (right).

Figure 16 The user viewing the virtual features visible in Figure 15.

fortification wall. This wall was about 2.75 meters thick, made of medium sized stones, with only several courses preserved. This structure was fully uncovered by the end of the 2022 season but removed in 2023 for deeper excavation. Our experiments with MR therefore replaced this crucial feature back into the trench to compare it to the walls of the earlier, deeper layers (Figure 11; Figure 12; Figure 13; Figure 14). We then placed the 3D model of a smaller adjoining wall, also from the Early Medieval period, that helped form a storage cellar built against the inner face of the fortification (Figure 15; Figure 16). Finally, we situated the 3D models of the inner and outer surfaces of a large ceramic storage vessel (pithos) that may have been in this storage cellar (Figure 17). We imported all these 3D models using either the .obj or .glTF (Graphics Library Transmission Format) file formats. This basic experiment worked well for both devices, but each had its strengths and weaknesses described in the following paragraphs, including sunlight visibility, field of view, spatial awareness, and limited boundary extent.

The HoloLens 2 screen is not bright enough to be visible under full sunlight. The only way we could use this device on the site was at dawn or dusk. Therefore, a small team periodically went out to the site at 5 am as the sun began to rise, providing about an hour of usable light levels (Figure 18). As mentioned above with the Blade 2, we are also planning to add sunglasses-type shades to the HoloLens 2, which have to be custom produced. The Quest Pro, on the other hand, has no problem with sunlight since it simply passes through the view from the cameras, so we could experiment all day. Although you can tell you are looking through cameras, everything is clear without much distortion and the graphics are sharp and can even be fully opaque (Figure 17).

Another major issue with the HoloLens 2 is the restricted field of view. This means that when you are in the trench, you must be looking almost directly at the digital 3D models in order to see them displayed on the screens. No digital models will appear in your peripheral vision, and the transition is an extremely abrupt rectangle. This makes the experience much less satisfying because you still see the entire real trench, but your graphics are cut off around the edges. The Quest Pro restricts your entire field of view, both of the real and of the virtual worlds, which provides a more seamless experience, even if constricting your natural peripheral view (Figure 19).

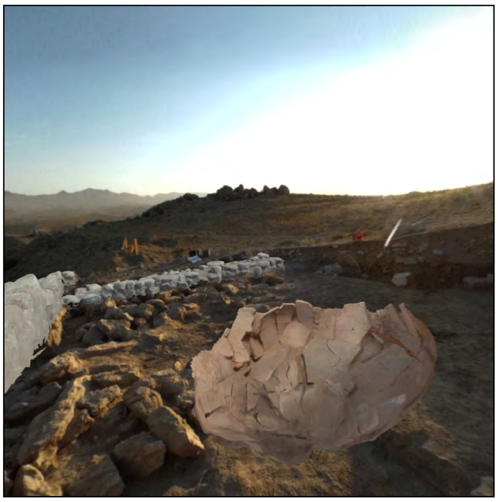


Figure 17 Quest Pro user view of the storage vessel and adjoining wall, from a different angle.

Figure 18 Team working in the early morning light.

At first, we manually scaled and oriented each 3D model while wearing the devices in the trench, and then we were able to view the models from different angles as they remained stationary within the real world (Figure 20). We could use hand gestures to 'grab' two edges of each model to rotate them or scale them by pulling our hands apart. However, we geolocate our photogrammetry models using targets measured with differential GNSS (Cobb, Earley-Spadoni, & Dames 2019), which means each 3D model can be automatically placed within the trench. Although the HoloLens 2 has spatial awareness, it does

Figure 19 Photograph through one Quest Pro screen.

Figure 20 Manually placing a model in the trench.

not know its position on Earth or even which direction it is facing. Thus, the only spatial information we can directly use from an original 3D model is its scale, with one digital unit becoming one meter in real life upon importation. For the Quest Pro, we need to set all the parameters of the model, including the scale, position, and orientation, when placing it into the real world. Although positioning each model manually is an option, this can lead to inaccuracies. Thus, we developed a solution that allows us to first establish the global coordinate system within the trench. We created three 3D models of flags to represent the locations of three corners of the trench and labeled each corner with its Universal Transverse Mercator (UTM) coordinates. When we brought the devices out to the trench, we placed these three virtual flags on the actual three corners of the trench (Figure 21). For the HoloLens 2, we actually only need to place two corners to set the horizontal position and orientation. After doing this, the local coordinate system of each device was aligned to the actual real-world UTM grid, and thus each of our 3D context models could be immediately imported with its proper location, orientation, scale in the trench. Hopefully, future MR devices will rely on internal and external dGNSS so that we can automatically and immediately load models into their real-world locations.

The placement of models in the Quest Pro was complicated slightly by the limited extent of the Guardian boundary. Although online forums claim that the boundary can grow up to 15 × 15 meters, and can even be disabled during pass-through, we were unable to achieve either of these situations. Instead, the largest practical Guardian extent we could lay out was only 6 × 6 meters, well below the full 10 × 10-meter extent of our trench. Since the Guardian acts as the spatial anchor for all models, any attempt to shift the extent to view other parts of the trench would cause all the models to move in unison (Figure 22). The HoloLens 2 does not have this limitation so we could see the full 3D models in situ whenever we looked directly at them.

For our next step, we plan to develop software that will integrate with our existing data management system, allowing users to load any 3D model while at any trench. To prepare 3D models, we synch raw image files for photogrammetry to our cloud-based Windows Remote Desktop server using OneDrive each afternoon. By the next day, trench supervisors can employ Agisoft Metashape on the server to initiate the building of each context's 3D model, about 2–3 per trench per day. Since a typical model, built at high quality, may contain about a million polygon faces, we down-sample each model to around one hundred thousand polygons or less, while maintaining a high-resolution texture, to balance visual quality at a useful scale with efficient file size. Given the limitations of the screen resolutions in the current headsets, these down-sampled models already provide a satisfactory viewing experience. Finally, we export the models as .obj files, making them available on the server by about two days after excavation, though we may later focus on developing ways to speed up this process if necessary. To get the models to the headsets, we are working on expanding our existing web service, which allows remote clients to access our central database, to include the serving of 3D models. Since each .obj file is usually up to 100 MB in size, this may raise concerns about the limited 64 GB local storage capacity of the HoloLens 2. However, it should be noted that a user would probably only be able to see about a dozen or so 3D context models at one time, with others hidden behind the visible models or in other trenches, so this should not be an issue even though most trenches have over 200 total context models. We are designing an interface that will allow users to load contexts on demand, which should take less than a minute even for the largest models to be downloaded over a 4G mobile connection. In addition to the inherent geolocational information in each 3D model, other metadata about each context can also be quickly retrieved from the central database using existing web service calls. The user interface we are now developing for the MR headsets will enable users to select which models to view through intuitive spatial interaction, based on their own location in the trench. This will open new and interesting human-computer interaction research that will be the subject of future analysis about our field experiments.

Figure 21 Placing a corner flag to set the coordinate system, HoloLens user view.

Figure 22 The limits of the Quest Pro's Guardian boundary extent.

5.3. EXPERIMENT 3: THE POTENTIAL FOR MR-GUIDED EXCAVATION

Our third effort was much more experimental, as we attempted to push the limits of what is possible and think of new ways of doing archaeology. We see opportunities for MR devices beyond just displaying data, where they could have a central role as active tools directly in enhancing excavation work. In our excavation, we often need to cut clean, flat surfaces to see better. This may be for the baulk sections but is often also for tracing horizontal layers, either at the end of removing basic dirt fill contexts or to make features or in situ finds more visible. Therefore, we had the novel idea that we might be able to use the MR headset to guide us in cutting perfectly flat surfaces at any angle. The same idea could be used, even more fundamentally, to carefully control the vertical ending depth while digging selected contexts. For example, if we wanted to excavate a horizontal layer exactly 20 centimeters deep, we could use the MR device for such depth guidance. Only the HoloLens 2 is currently capable of this functionality since it creates a polygonal model by 3D scanning existing real surfaces in real time. Thus, our programmer built a depth-guidance system to allow us to place a simple red flat plane horizontally (floor) or vertically (wall) within the real-world trench (Figure 23). The user determines where they want to excavate a flat surface and then they move the plane into place, even pushing it below the ground.

We experimented with using this depth-guidance functionality first to visualize the flatness of the already excavated south baulk of our trench (Figure 24). In the image, the red plane is visible where the real-world surface is located behind it and invisible where the real-world geometry covers that part of the plane. Thus, you can see that certain portions of the baulk section could be leveled better, though most of the complex topography is caused by stones. After examining the baulk, we next moved to using the MR depth-guidance system during actual excavation. We selected a raised area of dirt that we wanted to cut down to a surrounding flat surface about 15 centimeters lower. One team member first set the flat plane to the desired depth and then he actually dug while wearing the HoloLens 2, watching for the red plane to appear in a pit he dug from the center of the raised area (Figure 25; Figure 26). This experiment was a success as he ended when he saw the red plane, thus producing a precise depth of excavation. This depth-guidance function already works surprisingly well, even within the limitations of the existing technology. One could imagine other such uses for MR to guide an excavator through forming geometry within the real world or predicting what will come next in the trench. For example, perhaps the MR could indicate the likely line of an existing wall, virtually connecting the excavated portion to the unexcavated portion for the excavator.

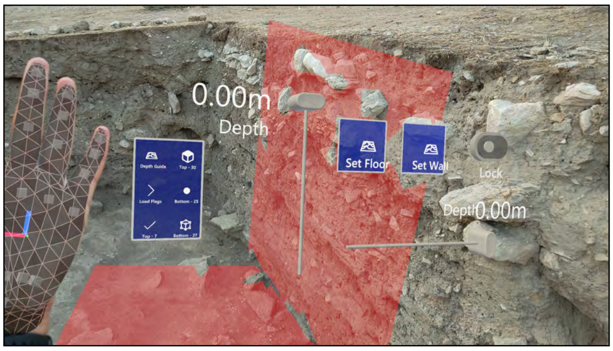


Figure 23 HoloLens depth-guidance system, user interface for placing virtual planes.

Figure 24 Measuring the flatness of the cuts of the trench baulk and floor.

Figure 25 Excavator preparing HoloLens depth guidance (left) and excavating with the system (right).

Figure 26 The HoloLens depth-guidance system sequence: **(a)** adding the flat plane **(b)** setting the desired depth **(c)** before excavation of the pit **(d)** the plane shows through when the desired depth is reached in the pit.

Such experiments that push the limits are necessary if we are to fully test the potential of the hardware. Another possible use for MR devices would be in the training of archaeologists, with virtual guides and even artificial intelligence (AI) enabled learning (Deru et al. 2023). This might be similar to the way Brondi et al. (2016) attempted to teach fine motor skills with the hands for heritage craftwork. Furthermore, similar to the experiment by Gaugne et al. (2019) to help excavators see 'inside' an urn, we believe that MR can directly find applications for guiding digging on-site, including tracing of geophysics data.

5.4. EXPERIMENT 4: MR FOR ARTIFACT ANALYSIS

The ever-increasing quantity of available 3D data about archaeological artifacts opens new opportunities for using MR during object analysis. In our final experiment, we set out to specifically try to compare real pieces of pottery with digital 3D models of related sherds. Using hand gestures that are tracked by the HoloLens 2, we were able to hold, through pinching, a virtual pottery sherd. We could then rotate and move the sherd within the real world. Thus, a team member experimented with puzzling together two large ceramic base sherds using the HoloLens 2 – one real and one virtual (Figure 27; Figure 28; Figure 29). This works reasonably well. However, the transparency of the virtual sherd makes the edges somewhat difficult to see as they can sometimes be obscured by the real sherd. We also tried joining sherds based on surface decoration (Figure 30) and comparing the profile of a real rim sherd with the profile of its virtual version (Figure 31). The HoloLens 2 actually worked better for this indoor experiment compared to those that took place in the trench, given the controlled lighting. In addition, the limited field of view was less of an issue since the sherds were close to the user and relatively small.

Figure 27 Using the HoloLens to virtually join a real pottery sherd with a 3D model.

Figure 28 HoloLens user view comparing real sherd (below) and 3D model (above), no scaling.

Figure 29 Joining virtual base sherd (left) with real sherd (right).

Figure 30 Joining sherds with surface decoration.

Figure 31 Comparing rim profiles, same sherd.

We could imagine using this method with other material classes like comparing lithic shapes or rejoining sculptural fragments. We should be able to compare or join the real objects from our site to virtual 3D objects scanned from other sites, storage areas, and museums, including those already shared online (Kobeisse 2023). Often times, such objects are difficult to access, either because of travel or permission restrictions. Another idea is that a real pottery sherd could be held within a virtual whole vessel to determine how well the shape matches or to determine the possible position of the sherd within the larger vessel. All these methods enable the type of embodied interaction with objects that specialists are used to, but they open new possibilities to work with precise data about objects that are remote or otherwise difficult to retrieve.

6. CONCLUSION

Our four experiments have provided a unique opportunity to test MR and AR hardware for a wide range of purposes in the field over the course of several weeks during an active archaeological project. The main strength of MR/AR is the potential to enable more intuitive ways to interact with, analyze, and share 3D data, even directly in the field. Although the hardware devices tested are not yet ready for daily use at the dig, we plan to continue experimenting through improving our software and acquiring the latest hardware. In our first experiment, we determined that AR smart glasses have the potential to be used for primary hands-free data collection. There are still some limitations with the hardware, but we have focused on developing user-friendly software that we will test in the field next season. Second, we have demonstrated that it is already possible to view previously removed contexts in situ within the trench. By examining these 3D models in place, we can better analyze the spatial relationships among the contexts and thus improve our interpretations while helping us plan where to excavate. We have solved the problem of precise placement though calibrating our local coordinate system based on locating three trench corners. Now, we are working on enhancing the ability for users to interact with the large amounts of data on our cloud server. Our efforts to push the limits of the technology into new applications, with our experimental depth-guidance system, also show promise. We can already measure the flatness of our excavation surfaces and excavate to a chosen depth. We can imagine further such opportunities for creative ways to use MR technology being explored by others in the future. Finally, the manipulation, comparison, and puzzling of both real and virtual objects in the lab is already possible with the HoloLens 2. For all these workflows, we still have to further develop software to support our archaeological practices. However, we continue to view the hardware limitations as the main current challenge to widespread experimentation and adoption of MR/AR for archaeological data collection and analysis.

Table 2 provides an overview of what we learned about the three hardware devices and their software. Among the primary challenges we faced, sunlight renders the screens of devices like the HoloLens 2 unusable during the day, and both this device and the Quest Pro are far too bulky to wear for extended periods of time in the dirt and heat. The Blade 2's form factor, on the other hand, is suitable for this environment, but lacks the full 3D interactivity of the MR headsets. We need hardware that can fit powerful processing into a small, portable, and comfortable format for a head-mounted device. An ideal device would combine the form-factor of the Blade 2, the visibility of the Quest Pro, and the functionality of the HoloLens 2. Industrial development of head-mounted immersive devices has occurred at a regular pace over the past decade and should continue, even if the exact trajectory of each product and company remains unclear (Robertson 2020). Already, since undertaking our initial experiments, new devices have become available, and others will also soon be released to the public. We have recently acquired several Meta Quest 3 devices, which have better color pass-through visibility and a larger field of view than the Quest Pro. We have also just acquired Apple's much-discussed Vision Pro device, which may encourage future developments of other MR devices, depending on how it is received. On the software side, we have thus far only had a chance to rapidly develop workflows specific to the initial experiments. The functionality has been sufficient, but

DEVICE	HARDWARE SPECIFICATIONS	SCREEN/FIELD OF VIEW	SUNLIGHT EFFECT	SOFTWARE	USER-FRIENDLINESS AND COMFORT
Vuzix Blade 2	AR Headset, only slightly larger than normal glasses; Battery may last all day; 40 GB storage; 8 MP front-facing camera	Small see-through screen visible through right-eye lens only, with no 3D graphics; 20 degrees FOV; 480 × 480-pixel resolution	Possible to use the screen in full sunlight, but clearer when looking towards a dark background; Adding sunglasses	Android 11 OS with simplified interface; Custom software for database entry at our excavation (based on the smartphone version), experimental voice-recognition text software	Interact with right index finger or verbal commands; Menu system is simple, but response time can be slow; Comfortable to wear for extended periods as it weighs 90 g
Microsoft HoloLens 2	Large MR headset with an open view; Battery can last 2–3 hours; 64 GB storage; 8 MP front-facing camera	Two see-through screens for immersive 3D view; 52 degrees FOV; reported 1440 × 936-pixel resolution per eye	Screen not visible in sunlight; Adding custom sunglasses	Microsoft Windows OS with floating touch menus; Custom Unity-based software for placing 3D models in the trench or lab; Software for voice-recognition journaling and photography	Relatively easy interaction with hand-gesture tracking and floating menus, quick enough response; Not comfortable to wear for long at 566 g
Meta Quest Pro	Large MR headset with a closed view and pass-through; Battery can last 2–3 hours; 256 GB storage; 16 MP front-facing camera	Two screens for immersive 3D, can see outside world through color camera feed; 120 degrees FOV; 1800 × 1920-pixel resolution per eye	No problems using the screen in full sunlight	Meta OS based on Android with floating touch menus; Custom Unity-based software for placing 3D models in the trench; Software for voice-recognition journaling and photography	Relatively easy interaction with hand-gesture tracking and floating menus, quick response; Not comfortable to wear for long at 722 g

Table 2 A summarization of the specifications and our evaluation of the three MR/AR headsets from our experiments.

more recently we have turned our focus to improving the software to build much better and more fluid user experiences that are integrated into our central data management system.

In our four experiments, we have put these three MR/AR headsets to work directly in our excavation trench for data collection and analysis purposes, something that has rarely been tried before. Our goal has been to demonstrate both what is currently possible as well as to provide a vision for potential future applications of these technologies at archaeological sites. We have had to put significant time and effort just into developing these initial experiments. While we have not completed everything and solved all the problems yet, it is what we learned from these efforts that we are presenting here to guide others at this early stage. By documenting and sharing the limitations of the current headsets, others can build upon our work, helping to solve select problems or test newer hardware, while exploring new research opportunities.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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