Visualizing and Assessing Hypotheses for Marine Archaeology in a VR CAVE Environment

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The understanding and reconstruction of a wrecks formation process can be a complicated procedure that needs to take into account many interrelated components. The team of the University of Cyprus investigating the 4th-century BC Mazotos shipwreck are unable to interact easily and intuitively with the recorded data, a fact that impedes visualization and reconstruction and subsequently delays the evaluation of their hypotheses. An immersive 3D visualization application that utilizes a VR CAVE was developed, with the intent to enable researchers to mine the wealth of information this ancient shipwreck has to offer. Through the implementation and evaluation of the proposed application, this research seeks to investigate whether such an environment can aid the interpretation and analysis process and ultimately serve as an additional scientific tool for underwater archaeology.

Categories and Subject Descriptors: H.5 [**Information Interfaces and Presentation**]—*Multimedia Information Systems*

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1. INTRODUCTION AND MOTIVATION

The important discovery of the ancient Mazotos shipwreck prompted the development of marine archaeology in Cyprus as well as the first Cypriot underwater archaeological project undertaken by the Archaeological Research Unit (ARU) of the University of Cyprus, under the direction of Dr. Stella Demesticha, in collaboration with the Department of Antiquities of Cyprus and the THETIS Foundation.

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Difficulties inherent within underwater archaeology hinder the researchers from forming and assessing research questions during the excavation process (before artefacts and evidence are lifted) and certain remaining limitations of the documentation data and the employed methodology [Demesticha et al. 2014] prevent them from interacting easily with the information gathered.

During an underwater excavation, all physical artefacts are permanently removed from their original position and context. Consequently, meticulous mapping and recording is of vital importance to ensure the accurate and thorough documentation of the site and the possibility of its future reconstruction. Once recovered from the underwater site, artefacts require special care, stabilization, and conservation.

Underwater sites are inevitably hazardous and difficult to access, which results in the excavation process becoming very time-consuming and demanding in human resources and specialized equipment. The Mazotos wreck can be accessed by divers but only for a limited 20 minutes of productive time, before they ascent. Work can be hindered further by many other factors such as narcosis, low visibility conditions, the dynamic nature of the environment, and weather conditions. Furthermore, the involvement of nonexperts, such as students and volunteers, also presents operational difficulties.

The excavation work is conducted vertically and in small sections, which impedes data from being spatially correlated, obstructs the archaeologists from forming a general impression of the site and from pinpointing obvious (to the trained eye) interrelated artefacts. This consequently slows down the process of data analysis and interpretation.

Underwater sites can be difficult to be experienced first-hand by the majority of other archaeologists, experts from different fields, or the general public. According to Martha Joukowsky, to fully understand a site and the relationships of everything, the archaeologist needs to be immersed in it [Vote and Joukowsky 2001]. Virtual reality can provide such an environment with realistic, 3D representation of data and can facilitate the exploration of varying perspectives and interpretations [Knabb 2008]. The focus of archaeology is to understand not only objects but events—the development of features and the transition from one stage to the next [Van Dam et al. 2000; Barceló 2001]—and immersive virtual reality may be an ideal vehicle for this.

A widely accepted definition of virtual reality (VR) [Rheingold 1991] describes it as an experience in which the user is surrounded by a three-dimensional computer-generated representation, is able to move around in it, to view it from different angles, and have the ability to reshape it. Apart from an intuitive interaction, a virtual environment can also permit a greater degree of movement for the user. Through the use of VR, data can become easier to understand, remember, and reference. User actions or observations, while immersed, can form a narrative for the user, thus enhancing the ability to recall data [Jacobson and Vadnal 1999]. User commands and inputs can instantaneously modify the virtual world and depict the effects of each change, thus creating a dynamic model. Real-time interaction is a key feature of VR, and archaeologists can use this to form hypotheses, perceive patterns, relationships, and so forth more quickly than by using maps, drawings, or photos alone [Barceló 2001].

Furthermore, the VR environment can be accessible to everybody—experts and the general public alike—in a relatively easy way when considering the difficult and demanding conditions that prevail, particularly underwater [Chapman et al. 2006; Allen et al. 2004].

The ARU researchers wish to develop a VR application to investigate whether and how the VR CAVE can be used as an additional tool for marine archaeology to aid and direct archaeological research, analysis, and dissemination as well as its potential as a learning and training tool. They also wish to investigate how the data produced for archaeological documentation purposes can be further utilized to form a virtual environment that facilitates the process of interpreting the site and its formation. In this article, we present a VR CAVE [Cruz-Neira et al. 1993] application developed in close cooperation with the ARU and the results of the user study, carried out with ARU members on a prototype of the application.

2. RELATED WORK

Archaeology employs procedures that are destructive in their nature. It is because of this key characteristic that archaeologists meticulously record and document sites with as much accuracy and detail as possible. It is common practice for archaeologists to use the documentation process deliverables to understand and be in a position to reconstruct the site at a later stage. Such a reconstruction derives from their need to interact with the produced data in order to explore the site and to understand the relationships between the elements that compose it and the stages of its transformation [Drap et al. 2012; Frischer and Hild 2008; Pansiot 2004].

The implementation of an effective immersive visualization tool that will further assist the scientific process of analysis and interpretation has been an obvious conclusion for many researchers [Allen et al. 2004; Acevedo et al. 2001; Demesticha et al. 2014; Barceló 2001].

2.1 Visualization

Visualization and computer reconstruction are widely accepted to be of great importance in the process of dissemination and presentation [Bernardes et al. 2012]. This is not the case with other processes and phases in archaeological research, with many archaeologists preferring to use more traditional means for visualization purposes. This reservation to use modeling and newer visualization methods for research and analysis is also evident in the work of other authors, such as Frischer and Hild [2008]. In contrast to this view, Barceló [2001] and Forte and Guidazzoli [as cited in Pansiot 2004] argue that through the use of such methods, the process of interpretation and analysis is facilitated; complicated and intricate data are presented visually and are made more easily comprehensible, permitting the testing of the validity of the reconstruction. Barcelo goes on to state that "the main reason for visual models is to help to see what the data seem to say and to test what you think you see." He adds that by building artificial objects and using them to act out scenarios, archaeologists gain improved insight into the data and learn by doing.

There is an evident reluctance, on the archaeologists part, to make assumptions and to reconstruct the history of excavated sites. There is a sense that this activity does not achieve a high level of accuracy and archaeologists are fearful of unfavourable criticism by their peers. This is precisely why the presence and expertise of the archaeologist is of paramount importance during this process and, even then, it proves a challenging task as many different interpretations and hypotheses need to be presented and evaluated [Roussou et al. 2003].

2.2 Archaeological Research Applications

The ARCHAVE [Vote and Joukowsky 2001], a GIS-based archaeological system that used a VR CAVE, provided researchers access to the excavation data of the Great Temple site in Petra, Jordan. This application aimed to help archaeologists interact with the data in order to perform research and analysis, develop ways for them to conduct queries, and assess the hypothesis that an immersive VR system would allow them to realize the potential of their documented data.

The VENUS project [Chapman et al. 2006; Haydar et al. 2011], developed by experts from various disciplines, aimed to improve the accessibility of deep underwater sites by developing virtual and augmented reality, immersive visualization tools for archaeologists and the general public. The archaeologists could improve their data understanding and study directly from within the virtual site.

The system implemented in a CAVE-like environment by Pansiot [2004], utilizing a database alongside an interface for navigation, developed an impressive assortment of widgets such as stick fields, density map, compass, rotative billboard, crop-marks, and terrain, which could be draped with different textures that enabled intuitive ways of understanding the environment. The systems objective was to facilitate the visualization of archaeological datasets in a range of representations through the interactive immersion of the user.

To the best of our knowledge, no similar work has been carried out regarding the use of the VR CAVE and its potential in the assessment of hypotheses concerning site formation processes or as part of the underwater archaeology methodology.

3. DESIGN AND DEVELOPMENT

The basic premise of the application design approach has been to engage the ARU team from the first steps of the design. This user-centred approach, aiming to produce an application with a high degree of usability, requires collecting and analysing as much information about the end users as possible, through a detailed user requirements process [Rogers et al. 2011; Gabbard et al. 1999; Drettakis et al. 2005] and a deep understanding of how they work.

3.1 User Goals and Requirements

The scope, user needs, content, information requirements, and functional specifications were defined through a number of meetings and interviews with the ARU team. The ARU were involved in every step of the design process through direct feedback, observation, and user testing. Discussions with key members of the ARU helped to clarify their research process and the traditional workflow employed and also become familiar with the Mazotos artefacts, documentation data, and published work [Demesticha et al. 2014; Demesticha 2011; Skarlatos et al. 2012].

3.1.1 *Traditional Workflow.* After multiple discussions with the ARU team and following them in their work, we made a number of observations regarding their workflow of examining hypotheses and interpreting the Mazotos site. The ARU team meets to exchange observations about the site findings and attempts to formulate and test hypotheses through discussions and by performing visual inspections of the documented data specific to each hypothesis.

The 3DSM as well as the point clouds allow the ARU team to visualize the site and artefacts and take metric data associated with an artefact as well as its relation to other finds in three dimensions. Likewise, site plans, maps, photographs, and drawings are used as tools to observe site features and excavated objects.

A marked problem of the existing methods is the fundamental inability to synthesize and examine data simultaneously, causing researchers to work in a constrained manner with each data format viewed and investigated, back and forth using several software. Members of the team with varying knowledge and skills in the use of the software retrieve photographs and individual artefact information from databases, loading the 3D site model and the point clouds in CAD, geographic information (GIS), and mesh processing systems.

This slow process is made more difficult due to large file sizes and existing limitations in the hardware. Processing and handling the 3DSM and point clouds close up on a computer screen causes the loss of perspective and visibility of the surrounding environment, making it harder for them to clarify relationships between artefacts and features. These factors result in the process becoming very time-consuming, tiring, difficult, and moderately efficient and considerably less effective in validating hypotheses. Finally, archaeologists feel that what is learned in front of the computer screen is something simply visual and one-dimensional and cannot be absorbed and treated in the same way as the experiential.

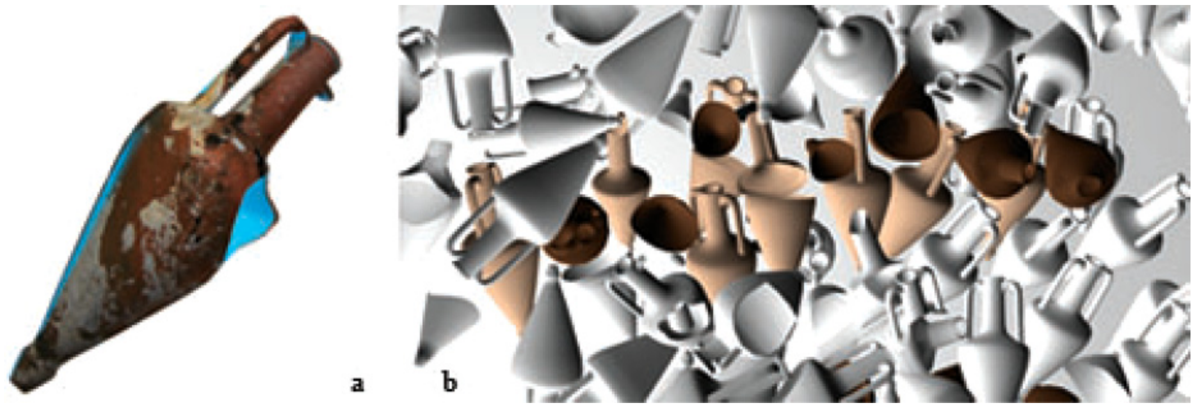

Fig. 1. (a) 3D model of amphora with texture, showing white traces to be examined for Hypothesis A. (b) The coloured amphorae indicate the amphorae to be examined for Hypothesis B.

The ARU team provided details for two of their current hypotheses regarding the site formation process,[1] which formed the focus of the application and are presented next.

3.1.2 *Hypothesis A (HA): Hypothetical Seabeds.* The Mazotos researchers are interested in examining the changes in seabed levels occurring at different stages of the site formation process. Data that may provide clues include white traces found on amphorae (see Figure 1(a)), the final positions of the anchor cores found in the bow area, and the documented superposition of shells and fragments of foreign artefacts. For this first hypothesis, they will need to be able to select an amphora, drape it with a texture created from the cleaned-up photographs, and mark it where the white traces appear on the artefact. Furthermore, they will have the added ability to expand these markings to create new or additional surfaces and check whether other artefacts' white traces are situated on the same level, which could imply a previous seabed. They wish to begin examining the distribution and correlation of such clues and divide the virtual environment into layers.

3.1.3 *Hypothesis B (HB): Amphorae Positions.* The second research question concerns the amphorae that lie in the centre of the bow area, described as found broken in situ, in a disturbed but not entirely disordered position and may indicate a wreckage episode or a phase of the deterioration of the ships hull by Demesticha et al. [2014]. At least four layers of amphorae seem to preserve their initial stowage position, which the researchers find extremely interesting. For the investigation of this research question, users will need to be able to re-create an amphora based on its fragments and to move it to new positions.

The primary design considerations for the application are:

—The application needs to provide an intuitive environment for users to work in and enable researchers to easily interact with the data, as the ARU researchers are unfamiliar with VR applications and would be using a VR CAVE for the first time. Furthermore, the ARU team consists of researchers from different backgrounds and expertise and, in some cases, different levels of familiarity and knowledge of the Mazotos site.

[1]Site formation process: The terms *site* or *wreck formation process* describe the many changes of state that occur to a ship, before reaching the seabed and what happens to it subsequently for the time it remains underwater, until it reaches an equilibrium with its new environment [Gibbs 2006].

—The archaeological team is looking for an environment that will allow the simultaneous and manageable viewing and comparison of the documentation process deliverables, which come in many different file formats and sizes. A virtual environment where spatial analysis can be done in three dimensions and users can see the relationship between the artefacts and surrounding features will allow the exploration of alternative perspectives and interpretations.

—For the application to be a valuable scientific tool, it must maintain a high level of accuracy and authenticity; this consideration has prompted the use of the original deliverables from the Mazotos shipwreck. Furthermore, any data received from the ARU should not be altered in any way, and all the original parameters need to be maintained (such as original dimensions or geo-referencing).

—An environment that can be enriched with new actual and hypothetical data, with every passing excavation period. The developed application would also need to allow easy addition and substitution of functionality.

3.2 Data Preparation

The original documentation data were received directly from the ARU for the purpose of this application and included:

—An Excel database of all information relating to the documented finds for the period 2010–2011.

—Photographs regarding amphorae to be examined for HA, taken at various stages of their excavation process.

—Four point clouds corresponding to the 2010 and 2011 excavation periods. The selected dense point clouds (in some cases more than 1 million points) had to be reduced in amount of vertices and converted into a mesh surface, using MeshLab.

—3D models created in Rhino of individual amphorae and of the entire reconstructed site to date. The amphorae examined for HA were coloured in blue and the amphorae for HB brown and cream to make them clearly identifiable to users. Even though the two hypotheses explained by the ARU involve predominantly the bow area, the rest of the 3DSM was also prepared to be used in the application.

The actual ARU data used in the virtual environment are superimposed with hypothetical information, designed and created specifically for this application and for the purpose of investigating and evaluating the use of the VR CAVE in the visualization and assessment of the two hypotheses. Newly created data, as seen in Figure 2, include:

—Amphorae textures: Texture maps for each amphora investigated for HA were created using the cleaned-up artefact photographs taken at the Larnaca museum.

—Predisturbance seabed: A semitransparent mesh, placed according to the artefact photographs, to indicate which artefacts and what parts of their bodies were found buried.

—Fixed amphorae: Some of the 18 amphorae examined for HB were only found in fragments, from which whole amphorae were re-created in approximation. These duplicated amphorae were coloured in cyan, indicating that they are hypothetically re-created data. The application will allow these fixed amphorae to be moved freely in the VR environment, enabling users to test hypothetical positions and spatial arrangements.

—Hypothetical seabeds: Once the texture maps were created, it was easy to see where the white traces appeared on the amphorae bodies. From this information, planes were created to indicate what hypothetical seabeds they would form if projected. Planes were also created and placed for the anchor cores, as their position may also indicate a hypothetical seabed. These semitransparent planes were

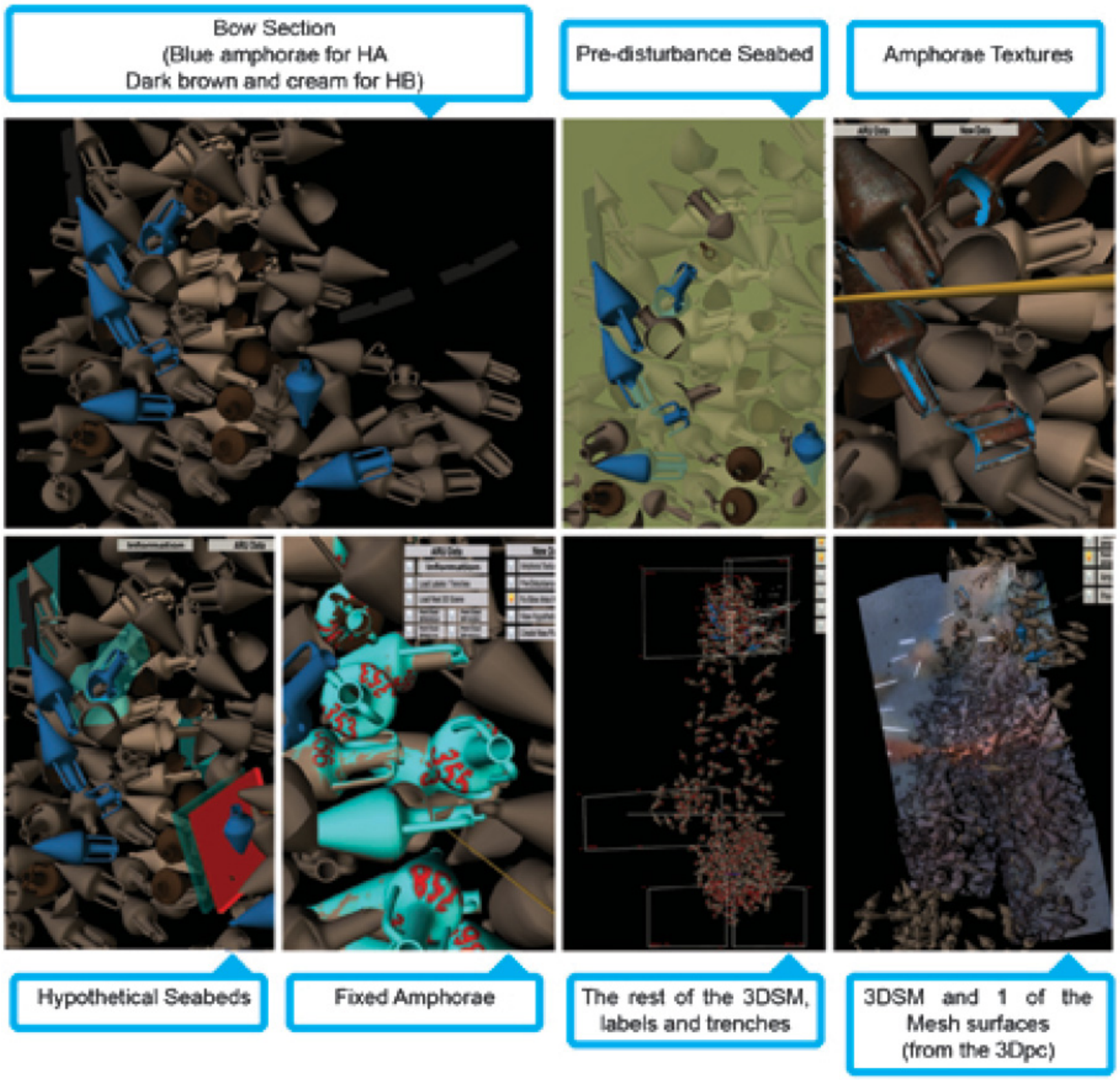

Fig. 2. Visualizing the Mazotos site documentation and hypothetical data, using the application.

created with the intent to allow users to move, expand, or contract them to visualize hypotheses regarding the site formation process.

—New plane: Users are able to create new semitransparent planes while in the VR environment and to manipulate them similarly to the hypothetical seabeds.

Once all the 3D models were ready, they were exported as eoz files using 3D Studio Max (through the EON Raptor plugin) to the applications authoring software EON Studio 8.

3.3 Design of 3D User Interfaces and Interaction Techniques

Designing usable and effective 3D user interfaces and 3D interaction techniques for VR environments, as well as the evaluation of applications using 3D user interfaces, can be a challenging task [Bowman et al. 2008]. Domingues et al. [2010] discuss that this is due to the rapid changes in hardware capabilities—the multiplicity and heterogeneity of VR devices—factors that have caused a lack of mature methodology in interaction design. Indeed, their assertion corroborates that by Bowman et al. [2001] who have subsequently carried out studies on how users interact with virtual environments as well as future prospects for 3D user interfaces [Bowman et al. 2004, 2006].

When designing the user interface and interaction techniques for the application, the following statement by Bowman et al. [2001] was considered:

> By taking advantage of the benefits of both 2D and 3D interaction techniques we can create interfaces for 3D applications that are easier to use and more intuitive to the user.

With this in mind, the application includes static 3D menus with dropdown options, icons, and information panels, providing a familiar metaphor for users.

Many factors influenced the decision to use an Xbox controller as the interaction device for the VR CAVE application. Research into other methods of interacting in VR (e.g., the use of a joystick or trackball, or voice command or gestures) have been found to be problematic [Cummings 2007; Nielsen et al. 2004; Stanney 1995]. Game controllers have also been found to be less intuitive to use [Duncan et al. 2006], but due to the key factors of freedom of movement and maintaining a correct feeling of immersion in the VR CAVE, a handheld device with conveniently accessible buttons and thumbsticks was considered suitable. Lastly, it was deduced that the Xbox controller would provide more degrees of freedom (DOF) to users with regards to navigation control during the use of the application and would also allow users to manipulate virtual objects through pointing (with the use of a laser beam, explained in Section 4.3), selecting, and manipulating.

4. IMPLEMENTATION

4.1 VR CAVE

The VR CAVE consists of four projection screens (three back projections for the walls and one front projection for the floor) and uses stereo projection technology and head tracking to display an immersive virtual environment. The system is controlled by four computers with Intel Xeon 64 bits CPUs at 2.60Ghz, each one responsible for one screen. The screens size is 2.44×1.83m and a projection resolution of $1{,}600 \times 1{,}200$ pixels.

With the use of a NVidia Quadro 6000 graphics card on each computer, active stereoscopy is possible with a refresh rate of 120Hz; 60Hz for each eye. The synchronization of the frames between the four screens is achieved with the NVidia's frame lock technology. For the users to perceive the stereoscopic images, active stereo glasses are provided.

Via a Vicon tracking system, consisting of four infrared cameras, 6-DOF tracking is allowed for the head and the controller in the $2.50\text{m} \times 1.85\text{m} \times 2.50\text{m}$ area. The users head is tracked by markers placed on 3D glasses (see Figure 3(a)), providing essential information to the system to correctly render the scene based on the user's point of view. The user is also equipped with an Xbox controller (see Figure 3(a)), which is tracked in the same manner and is used for navigation and manipulation of the virtual environment.

The VR CAVE currently supports EON Studio as the software API for the design, development, and presentation of VR applications. EON Studio 8 provides a library of predefined nodes and prototypes with ready-made functionality (such as for tracking, displays, and Xbox controller navigation), which

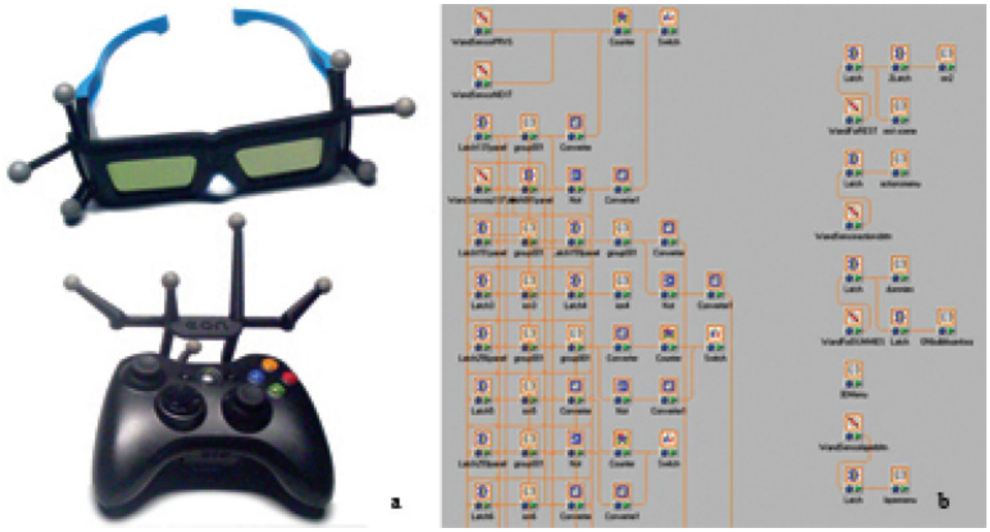

Fig. 3. (a) The 3D glasses and Xbox controller used for the purpose of this application, both equipped with markers, which enable tracking in the VR CAVE. (b) The Routes section of the EON Studio environment, showing some of the nodes and prototypes used to form the interaction for the information panels and the menu buttons.

were used to add interactivity. These nodes and prototypes are then connected with the 3D models and user interface in the Routes section of the EON Studio 8 environment (see Figure 3(b)) to provide the functionality and interactivity for the developed application.

This graphical authoring tool, catering for non-programmers and programmers alike, was found easy to learn and use. With the advantages of preprogrammed functionality, quick import of most generic CAD and 3D formats, the ability to quickly alter and reuse content, and its compact file format, this tool helped to minimize the development time needed for the application. It took 4 man-months to design and develop the VR application for this study, from the user requirements specification phase to the user testing phase.

The EON systems functionality can be further extended in many ways, such as using script language (Jscript, VBScript) to create custom nodes and prototypes or by connecting an application with database information. Furthermore, it can be integrated with other standard software or deployed over the Internet or as a standalone.

4.2 User Interface

The interface is comprised of menus, icons, and information panels (see Figure 4), through which the user can enable different data and supportive material to be loaded in the virtual environment. The information panels supply the user with information regarding the artefacts, extracted from the Excel database. In addition to the description, material, date lifted, and dimensions, each information panel presents the selected photographs corresponding to each artefact, ranging from it being undisturbed underwater to its process of excavation, lifting, and cleanup at the museum.

4.2.1 *Data and Supportive Material.* A number of data and supportive material that can be categorized as ARU Data, New Data and Supportive Material can be loaded by the user when using the application.

ARU Data are the real data received directly from the ARU: the information regarding artefacts to be examined in relation to HA and 3D meshes in the form of artefact labels and excavation trenches,

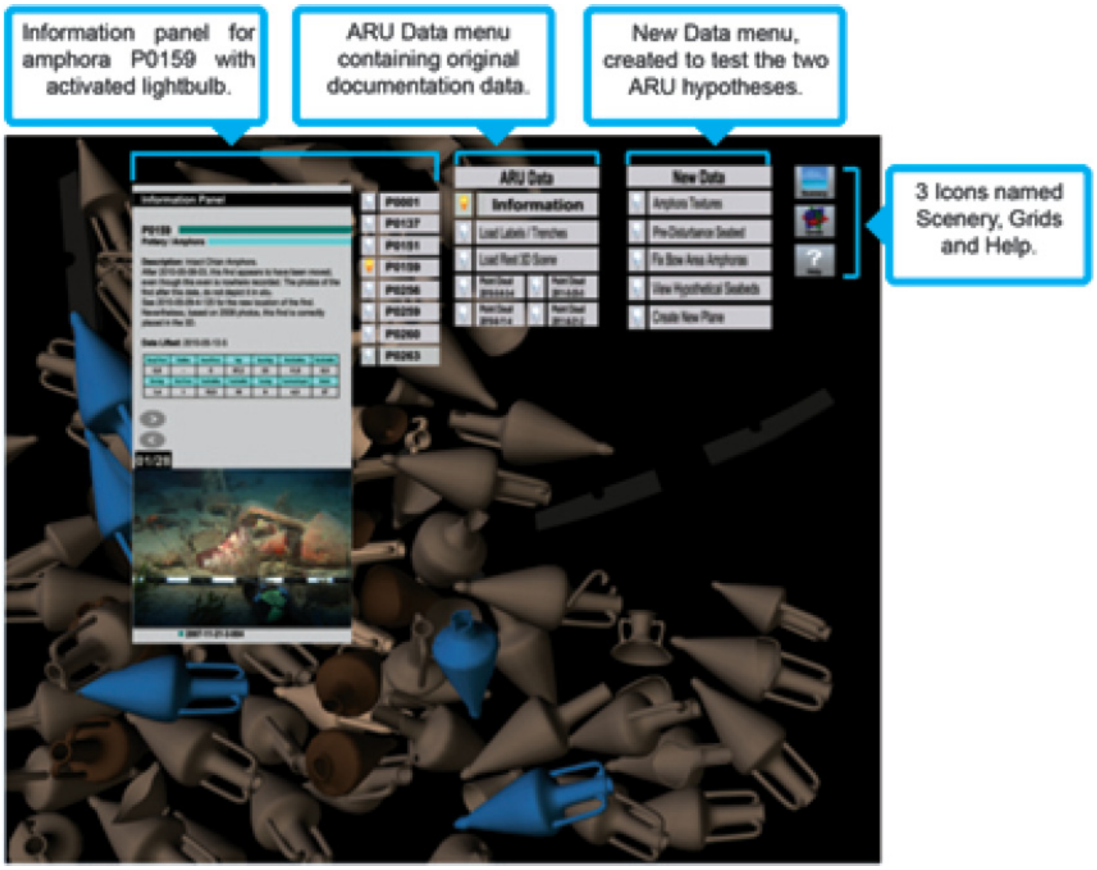

Fig. 4. The menus, icons, and information panels that make up the interface.

the complete 3D site model, and the four point clouds (described in Section 3.2). New Data are the hypothetical data created specifically for this application to assist users in visualizing their hypotheses. These include the amphorae textures and predisturbance seabed, the fixed amphorae for HB, hypothetical seabeds, and new planes, which were described in Section 3.2.

Finally, Supportive Material can be loaded through the icons provided in the interface (see Figure 4). When the user activates Scenery, the black background is replaced with artificial scenery as a way of adding landmarks to the virtual environment to support the user in case of difficulty in understanding his/her movement, viewpoint, and orientation. The Grids icon activates three grids (coloured red, green, and blue to indicate the X, Y, and Z axis, respectively), each consisting of 400 squares (20 × 20 of 1m × 1m). The grids were added so that the user can manipulate, move, and scale objects with more accuracy in the 3D environment. Lastly, the Help icon activates a series of help screens that appear to explain the application and support the user during its use.

4.3 Interaction

To enable users to interact with the interface and the objects that populate the virtual environment, we implemented simple ray-casting [Mine et al. 1995] through the use of an Xbox controller.

In the virtual world, a laser beam is used to indicate the direction the controller is pointing at and is an essential part of how the user is allowed to interact with the virtual environment. The laser beam can be activated/deactivated by the user through the start button on the controller.

The available interaction can be divided into two types: for navigation and for actions. Through the navigation controls, users are allowed to navigate in the environment to explore and view its elements from different vantage points and proximity. The controller's right stick allows the user to move forward, in the direction of the laser beam, and backward, left, and right in the virtual world. Additionally, upward and downward movement can be achieved using the left stick while the left and right back triggers rotate the environment either left or right in respect to the Y axis.

Ten pre-saved locations are also available, giving the opportunity to the user to change views quickly and easily while examining the site. Some of these locations enable the user to view the 3DSM as a diver would from above, and others allow easy movement through the assemblage as if walking through it. The navigation using the pre-saved locations can be achieved, using the left and right bumper buttons on the controller.

Using the A, B, and Y buttons on the controller, users can perform actions, either to interact with the interface or to manipulate some of the 3D objects within the scene in various ways. The fixed amphorae for HB can only be moved in the 3D space (6DoF), whereas the hypothetical seabeds and new planes can also expand or contract. The objects that can be manipulated, highlight in red when the laser beam is directly pointed at them; upon selection, each object can be moved freely, following the laser beam until it is released by the user.

5. EVALUATION

Once the first prototype was ready, a heuristic evaluation took place so as to identify usability problems; two usability experts carried this out. During the evaluation session, the evaluators went through the user interface of the application, inspected its various elements, and compared them with a list of given usability principles or heuristics [Sutcliffe and Gault 2004] for VR applications. The findings led to the improvement of the interface and the application itself and eventually to a newer version of the prototype.

The evaluation methodology selected for this study draws from the structured framework discussed in several surveys [Bowman et al. 2002; Hix and Gabbard 2002; Gabbard et al. 1999; Livatino and Koffel 2007; Bach and Scapin 2010] for conducting user testing to evaluate virtual environments. This includes the combination of user needs analysis, user task scenarios, usability evaluation, and formative evaluation, prior to a summative evaluation. This method was selected taking into account three characteristics: the involvement of representative users, the context of evaluation, and the types of results produced. It was also chosen in order to collect both qualitative and quantitative data and to gain insight into the effectiveness and efficiency of the prototype.

The heuristic evaluation was followed by a formative evaluation, which is typically conducted during the development or improvement of an application. Tasks were designed to determine whether the application is usable by the intended users to carry out the visualization and assessment of the two hypotheses for which it was designed (see Figure 5). This method gives insight into how each user will tackle these tasks while in the VR CAVE, how they will respond, their actions, cognitive status, always in conjunction to how the application performs. Moreover, through this method, required functionalities that are missing in the prototype could be pointed out. The users were asked to perform the following tasks:

—Navigate through the virtual environment
—Display information and images related to an artefact

Fig. 5. Photographs taken during the evaluation; the user on the left is examining hypothetical seabeds and the one on the right is moving a fixed amphora.

—Individual artefact selection
—Load amphorae textures
—Load and manipulate hypothetical seabeds
—Load the predisturbance seabed
—Load and manipulate fixed amphorae (moving and rotating them and positioning them in a predefined location using the grids)

A pilot test was conducted to test the feasibility, equipment, time needed to complete the tasks, and methods prior to the actual evaluation. The methods used in the evaluation included a pre-test questionnaire, direct observation, a post-test questionnaire, and semi-structured interviews in order to achieve methodological triangulation [Rogers et al. 2011; Livatino and Koffel 2007].

The pre-test questionnaire concerned participant skills and habits regarding computer usage and VR experience. Nine users (three male, six female) took part in the evaluation study, with three age groups equally represented (21–30, 31–40, and 41–50). With regard to their general professional experience, two had extensive experience of 14 and 20 years, respectively, three had 4, 5, and 7 years, respectively, and two did not give information. The majority of the participants rated their computer skills as average, three as good, and one as excellent. The majority (five participants) had not used VR before.

5.1 Usability

The questions contained in the post-test questionnaire were derived from existing questionnaires [Kalawsky 1999; Slater et al. 1994; Witmer and Singer 1998]. This questionnaire served to ascertain what the users thought of their interaction, their overall impressions, and to get their feedback on the more technical aspects of the specific VR application. For this reason, the post-test questionnaire was also divided into seven sections in terms of Interface, User Input, Application Output, User Guideline and Help, Consistency, Immersion/Presence, and Overall Impressions. The participants were asked to rate the difficulty (using a 5-point Likert scale) of the aforementioned aspects and their level of satisfaction with the interaction. The following analysis is based on the results of the questionnaires as well as archaeologists comments (spontaneous thinking aloud) during the test as noted by the experimenters.

5.1.1 *Interface Functionality.* Overall, there were 75% positive reactions for this category. It is clear from the answers that everybody found the functionality of the application easily accessible. Furthermore, seven users found it appropriate for the task. One of the participants (11%) definitely did not use all the functions provided, but four (55%) did, with the remaining users either undecided or not responding. When asked how successful they were in performing the tasks, 88% responded positively and the remaining user did not answer.

5.1.2 *User Input.* In this section, we have the biggest density of undecided and disagreeing scores, compared to other categories of the questionnaire, with the overall user response being about 53% positive. Of the participants, 77% found the Xbox controller easy to use, but the remaining 22% were undecided. In addition, 44% felt they made no mistakes and had the right level of control, whereas 33% were undecided and 22% responded negatively. When asked how easy they found it to select and move objects, 44% responded favourably, 44% negatively, and 11% were undecided. Fifty-five percent found it easy to position themselves in the VR environment, 22% were undecided, and 22% did not find it easy. When asked whether they would prefer an alternative input device, 33% were undecided, 11% disagreed, and 55% agreed.

5.1.3 *Application Output.* The majority of users found the display device—the use of the VR CAVE—appropriate for the tasks, with 77% positive answers overall. Seventy-seven percent did not feel nauseous, and 55% felt that their eyes were fine after using the application. The objects contained in the application were found to be realistic by 77% of the users; 88% considered the displayed information to be simple. When asked how well they could examine elements within the virtual environment, 77% responded well and 22% with somewhat.

5.1.4 *User Guidance and Help.* Overall, there were 81% positive reactions for this category. Eighty-eight percent felt the application was easy to learn, but 11% disagreed. The same answers were given when asked whether they found the application easy to use. Of the users, 66% felt the need for further help when using the application, 22% did not, and 11% were undecided. When asked whether they had felt confused or disoriented when using the application, 88% responded that they had not and only 11% gave the answer somewhat.

5.1.5 *Consistency.* In this section, the concentration in positive (agree and strongly agree) options is the greatest, with overall reactions being 94% positive. All users found the application responding as they expected, and all thought that their actions matched their understanding of the task. Only one participant did not find the information and the use of icons/menus/toolbars displayed by the application consistent. When asked if they found the application clear and simple to use, 88% agreed.

5.1.6 *Immersion and Presence.* This section also obtained a strong concentration (74% overall) of positive agree and strongly agree answers. The results were similar for the two statements asking the participants to indicate how immersed they felt in the virtual environment and whether they felt as if they were at the Mazotos site, with 66% responding positively, 11% negatively, and 22% undecided. The majority of users (77% and 88%, respectively) found that the quality of the image and the field of view enhanced their sense of presence, whereas eight users found it easy to move around in the VR CAVE. Finally, 55% responded that the application and the VR CAVE gave a good sense of scale, with 22% disagreeing and the rest undecided. When asked how natural their interaction with the environment seemed, 44% found it natural, 44% found it somewhat natural, and 11% found it not very natural.

5.1.7 *Overall Impressions.* All participants felt they can work easily in 3D and enjoyed using the application. Seventy-seven percent felt they had a clear idea of how to perform a particular function, but the other 22% disagreed. The majority of users (88% positive answers and 11% undecided for each of these questions) were impressed with the interaction, felt they achieved what they wanted from the application, and found the VR environment simple. When asked whether they would feel comfortable using the application/VR CAVE for long periods of time, 66% responded positively and the remaining did not know. Finally, as to the applications usability, 55% rated it very satisfactory, 33% as satisfactory, and 11% rated it as unsatisfactory. All nine users think that the application will help the Mazotos research, two of them think much and the remaining seven very much.

The results showed a trend: the younger users responded more positively than the older ones when rating their experience of using the VR CAVE application. The former tended to agree that their interaction felt more natural, that the Xbox controller was easy to use, and that the application provided them with the right level of control. On the contrary, the older users responses show a tendency of being less convinced regarding the same points. This is probably attributed to the user's role in the investigation, specifically the older users involvement in the decision making and design of the research, whereas the younger group is more involved in the implementation aspect of the research. Decision makers tend to be more experienced and, therefore, look at things in greater detail; thus, they are generally more demanding.

5.2 Interview Results

Semistructured interviews were conducted to gather qualitative data from the representative users to reveal more information regarding three key issues of interest: the perceived effectiveness and suitability of the application in assessing ARU hypotheses, how the documentation deliverables could be further utilized, and finally the perceived suitability of the VR CAVE as a tool for the Mazotos project and research.

5.2.1 *The Application as a Tool for Testing Hypotheses.* During the interviews, all users were unanimous in their belief that the developed application is very useful in the process of interpretation and in the assessment of hypotheses and that they were able to successfully complete the tasks.

The users considered the application to be a useful research tool for the archaeologists and all the other professionals working on the Mazotos project. In terms of research, the great advantage that was agreed upon was the scale, as it enabled users to view and examine complex and visually rich data (mesh surfaces of point clouds) with ease and from new vantage points, alongside the other documentation deliverables. The loading of amphorae textures was found extremely useful in visualizing and assessing hypotheses regarding the site formation process. One of the users explained that by moving the amphorae around in countless experiments, ideas regarding their stowage will in turn give birth to fresh archaeological questions (e.g., the ropes used, their number, how they were fastened). The process of visualizing and investigating a research question quickly and efficiently generates further questions just as quickly.

On the other hand, there are doubts whether clear, accurate answers can be obtained from using the application alone, as the ARU users believe they can only trust physical evidence. They would not base any conclusion exclusively on the application. They would always use it in correlation with the shipwreck and physical evidence as a way to ensure better results. Describing a natural inertia to the new and instead preferring the methods they are used to, they agreed that they should be insisting on using the VR application, developing it, and training in it as a way to understand how the VR can assist their work and research.

When comparing the VR CAVE application with their traditional workflow, all users found the former more time-efficient, and the fact that it enables them to view all types of data simultaneously in one environment was a great advantage. Moreover, investigating the virtual site in the VR CAVE is much closer to the feeling of examining the actual site underwater than any other method used presently. It opens new ways of investigation and aids in their research. They agreed that the feeling of immersion helps on all levels, creating a frame of mind, writing the thought process of all the research involved, and transmitting the research process well. The application enabled them to easily understand the spatial relationship of the artefacts and find any mistakes in the documented data. The fact that you can see and experience everything together and on land facilitates the interpretation and assessing of hypotheses.

The users also had suggestions for improvements to be incorporated in the application in order to improve the current version of the prototype. They expressed their wish to see further data incorporated in the application such as the environmental information available regarding currents, the sedimentation, the hardness of the seabed, the various layers and levels of excavation, and many other elements. They believe that interacting with these newly proposed elements will fuel more questions and hypotheses and that there is a great potential to make the most of all available data and information.

Furthermore, if additional information is incorporated, which is not currently in the possession of the ARU, such as data from biologists, oceanographers, and other disciplines, this would lead to new insight regarding the site formation process. Each additional piece of relevant information will increase the interaction, shed more light, and facilitate the process of data analysis and interpretation.

5.2.2 *The VR CAVE as a Tool for Marine Archaeology.* Because researchers are away from the site when they perform the analysis and interpretation and try to answer questions regarding the site formation process, the users quickly saw advantages in using the VR CAVE. They agreed that the feeling of immersion creates a frame of mind, writing the thought process of all the research involved; it transmits the research process to the team and to the public at large. They felt that immersion helps on all levels and that the application in the VR CAVE should be developed further.

The participants commented that the type of investigation provided in the VR CAVE environment, is the closest method to the original underwater experience they have tried so far. It opens new ways of investigation and helps research. The advantages of immersion and scale of visualizing the Mazotos site in the VR CAVE enables researchers to understand spatial relationships and examine the documented data with greater ease while interacting with it in a more natural and intuitive way. Without time constraints, researchers could cover more ground more thoroughly and explore the site either all at once or in sections.

The VR CAVE was considered a good environment for productive collaboration with other experts from different disciplines as the assessment of research questions requires the insight and knowledge of shipbuilding experts, engineers, and others as well as a powerful dissemination tool for the public. Data collected from years of excavation, thousands of dives, and enormous work could be presented effectively.

The users highlighted the usefulness of this method for training and orientation of new researchers and other associates who do not dive or before they dive. It would provide a novel way to prepare, to have an overview, to understand the site and how to tackle it, and, more importantly, to understand what the archaeologist wants to achieve and the objective of each dive.

The VR CAVE was considered an interesting tool with which to investigate how the archaeologists observe the shipwreck: considering their interaction with the 3D model, then with the application, simulating how they would interact on site, record their research questions, what they consider issues of priority and urgency, and how they would tackle them. The users expressed the concern that using the VR CAVE for long periods of time would be tiring and agreed that having to go outside the office can be cumbersome. As the VR CAVE is not available at the ARU offices or closer to the Mazotos site, it cannot be used continuously by the researchers, but probably before and after excavation periods.

The researchers would need to come to the VR CAVE prepared, with more recorded evidence from the museum or other information that they would want to assess using this technology and application.

5.3 CONCLUSION AND PERSPECTIVES

The work described in this article has been concerned with the design, development, and formative evaluation of an interactive and immersive application specifically for the Mazotos shipwreck in Cyprus and utilizing the VR CAVE, with the intent to investigate whether and how this technology could be useful in visualizing and assessing hypotheses for marine archaeology.

It was observed that during the formative evaluation sessions the ARU researchers interacted easily with the documented data that made up the virtual environment and were successful in completing the evaluation tasks. The evaluation confirmed that the ARU found the prototype application, and the VR CAVE by extension, a useful, additional tool for underwater archaeology that can facilitate in the testing of hypotheses, research, analysis, and dissemination, with the potential to be used as a learning and training tool.

The results of this study agree with the findings of both Pansiot [2004] and Vote and Joukowsky [2001] that the representation of large amounts and various sources of data within the same immersive virtual environment can greatly facilitate archaeological analysis and seems to be a key feature of an efficient archaeological virtual environment. This study's findings also corroborate the assertion made by Barceló [2001] and Forte and Guidazzoli [as cited in Pansiot 2004] that through the use of modeling and newer visualization methods, complicated and intricate data can be presented visually and made more easily comprehensible, thus also aiding archaeological research and interpretation.

The results of this study were derived from the user testing of the application in its latest version, with an unavoidably small number of users. We argue that they are rich results, as they involved an in-depth observation of the users' traditional workflow and a VR application designed with the direct involvement of the actual users. However, deeper evaluation needs to be performed to compare immersive and non-immersive VR demonstrators and assess the benefits of immersive VR as seen in the evaluation process of Haydar et al. [2011]. The authors believe that two additional aspects emerging from the user studies would be interesting to explore in the future: (1) teaching and training archaeology students using the VR CAVE application, and (2) implementation and assessing more intuitive ways and input devices for users to control the virtual environment.

We will use the results of this study to further develop the application in close cooperation with the ARU team, with further functionality added to aid in the visualization and assessment of their research questions. Continuing the iterative process, new and useful features will be added with each successive version of the application and evaluations will be conducted to isolate issues and implement further improvements.

Ideas for additional functionality were mentioned during the user evaluations, including the ability to leave annotations in the environment, to leave marks on amphorae and other artefacts, finding a way to indicate distances in relation to a stable point, and the further re-creation of artefacts from fragments found. The process of examining an artefact more closely would be simplified by having the option of isolating it from the rest of the scene. The ARU researchers would also be interested to see different texture maps per amphora from different excavation stages (i.e., when undisturbed underwater, lifted with debris still attached, cleaned up at the museum). The existing functionality for moving and manipulating the 3D objects will also need to be extended to permit users to do so through numeric input. Further iterations of the application will need to handle larger amounts of data and we strongly believe that the possibility of connecting the VR CAVE application to a database needs to be investigated.

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