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Virtual Exploration of Underwater Archaeological Sites : Visualization and Interaction in Mixed Reality Environments

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Abstract

This paper describes the ongoing developments in Photogrammetry and Mixed Reality for the Venus European project (Virtual ExploratioN of Underwater Sites, http://www.venus-project.eu). The main goal of the project is to provide archaeologists and the general public with virtual and augmented reality tools for exploring and studying deep underwater archaeological sites out of reach of divers. These sites have to be reconstructed in terms of environment (seabed) and content (artifacts) by performing bathymetric and photogrammetric surveys on the real site and matching points between geolocalized pictures. The base idea behind using Mixed Reality techniques is to offer archaeologists and general public new insights on the reconstructed archaeological sites allowing archaeologists to study directly from within the virtual site and allowing the general public to immersively explore a realistic reconstruction of the sites. Both activities are based on the same VR engine but drastically differ in the way they present information. General public activities emphasize the visually and auditory realistic aspect of the reconstruction while archaeologists activities emphasize functional aspects focused on the cargo study rather than realism which leads to the development of two parallel VR demonstrators. This paper will focus on several key points developed for the reconstruction process as well as both VR demonstrators (archaeological and general public) issues. The first developed key point concerns the densification of seabed points obtained through photogrammetry in order to obtain high quality terrain reproduction. The second point concerns the development of the Virtual and Augmented Reality (VR/AR) demonstrators for archaeologists designed to exploit the results of the photogrammetric reconstruction. And the third point concerns the development of the VR demonstrator for general public aimed at creating awareness of both the artifacts that were found and of the process with which they were discovered by recreating the dive process from ship to seabed.

Categories and Subject Descriptors (according to ACM CCS): J.2 [Computer Applications]: Physical Sciences And Engineering

1. Introduction

Underwater archaeological sites, for example shipwrecks, offer extraordinary opportunities for archaeologists due to factors such as darkness, low temperatures and a low oxygen rate which are favorable to preservation. On the other hand, these sites cannot be experienced firsthand and are continuously jeopardized today by activities such as deep trawling that destroy their surface layer.

VENUS is a multidisciplinary project funded by the European Commission, Information Society Technologies (IST) programme. The main goal of the project is to provide scientific methodologies and technological tools for the virtual exploration of deep underwater archaeological sites by improving the accessibility of underwater sites and generating thorough and exhaustive 3D archives [CCD*06]. Therefore, VENUS is developing virtual and augmented reality tools for visualization and immersive interaction with a digital model of an underwater site as an example of digital preservation and for demonstrating new exploration facilities in a safe, cost-effective and pedagogical environment. The VENUS consortium, composed of eleven partners, is pooling expertise from various disciplines: archaeology and underwater exploration, knowledge representation and photogrammetry, virtual reality and digital data preservation.

Section 2 presents improvements of the seabed obtained through the photogrammetry process in terms of meshes densification and high resolution texturing. Sections 3 and 4 introduce VR application developed for archaeologists and section 5 introduces an evolution from VR to AR of this application. And finally section 6 presents the development of the VR interface for the general public recreating the dive process.

2. Virtual seabed enhancement

Getting a dense mesh for the seabed terrain have different purposes, first of all it can be useful for building an accurate orthophoto of the site on an uneven terrain, and further on it drastically enhances the realism of the reconstructed site within both VR demonstrators.

2.1. Seabed densification

The surface densification process starts from a set of points, manually measured, describing the 3D object to be surveyed in a relevant way. This cloud of point is first triangulated and then each triangle became a guide for new point generation in a regular grid. Each triangle is scanned with a given resolution and the points are projected on an image reference (a first draft version of this approach have already been published in [DFGP06]). Then we use the other projection of these points on other photographs as an approximate value for a correlation process (See [Kra97] page 354 for details on correlation). The final 3D point can then be seen on a large number of photographs and is computed with accuracy. We performed a set of tests and threshold to reject false correlation due, for example to correlation on moving algae's or fishes. This algorithm produces a high number of well organized points, but need to be processed on photographs with a correct local contrast to ensure correlation efficiency.

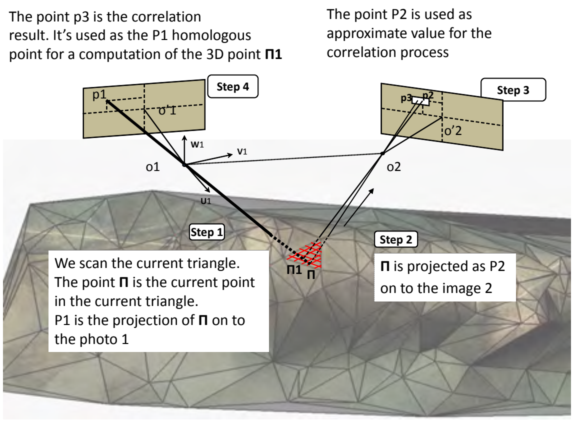


Figure 1: Densification scheme

We employed four steps (see Figure 1) in this surface densification method, considering that a mesh has been measured and computed from a set of 3-D points visible on at least two images:

1. Each triangle of the mesh is scanned to get point Π. Each point Π is projected as p_1 on photograph 1;
2. Π is projected as p_2 on the second image;
3. Point p_2 is used as an approximate position to initiate the area based correlation process with p_1;
4. Point p_3 is the result of the correlation; p_1 and its homologous p_3 are used for the computation of the 3-D coordinates of Π_1.

2.2. Results on Pianosa

The first experiment on the correlation densification process was done on data from the Pianosa site [DSGG08]. The covered surface is about 20×20 meters covered by 291 photographs. The densification process start an initial set of 2816 points used to orient the photographs, then the first step is a Delaunay triangulation of the surface and then a scan of each triangle with a 1mm step.

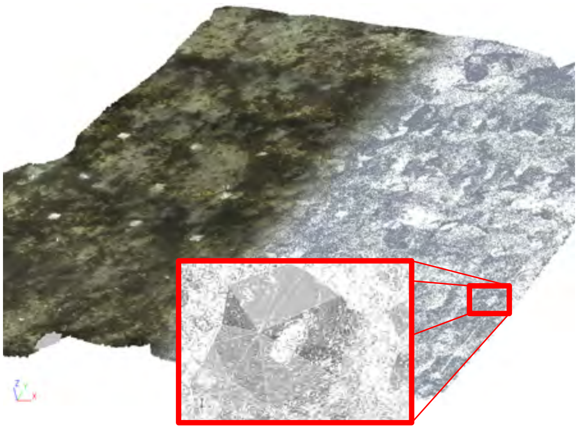


Figure 2: Densification process done on Pianosa site

The densification process (see Figure 2) produces 3586959 new 3D points and 4168954 have been rejected for correlation problem or by epipolar constraint on the third photograph. All the points have been computed on at least 3 photographs, with a minimum correlation coefficient of 0.7 and a residual error on epipolar line less than 3 pixels. We also know that final points can't be farther than 0.1 m from the original triangles which provides a mean accuracy of 5mm (the photographs have been taken by divers at 2 meters away from the seabed). The ultimate problem for the moment is performance as the process is still time consuming (around 39 hours for the entire densification) but we are currently working on to improve these aspects.

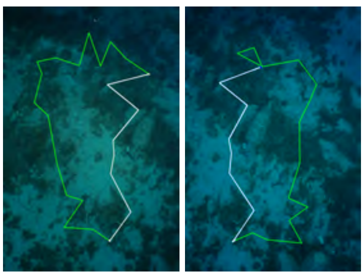
2.3. Seabed texturing

In addition to seabed densification, the resulting meshes has to feature high quality textures in order to be considered as useful as large original photos by archaeologists within the virtual environment. Besides, since textures are using these original photos, they might feature a strong vignetting effect due to insufficient lighting during shot time (see Figure 3(a)) and therefore strong luminance discontinuities might appear on the edge of each seabed part (see Figure 3(b)).

(a) (b)

Figure 3: (a) Image from real seabed. (b) Texture from digital seabed

In order to reduce textures discontinuities along the edges of seabed parts a blending algorithm have been carried out on the images used before texturing the seabed. Many related works have proposed simple linear blending methods or more complex blending methods. Clipmaps introduced by Tanner et al. in [TMJ98] provides an efficient technique for displaying very large textures. However, a large amount of texture memory is used, and a large texture must be obtained or created before use. Döllner et al. in [DBH00] present a flexible Level of Detail (LOD) technique for texturing terrain with multiple layered textures. The presented technique allows portions of different textures to be viewed selectively over different portions of terrain. However, the texture covers the entire terrain and is not built from tiles. As texture buffers in common current hardware hardly reaches 4096×4096, we have to use multiple buffers (an also images) in order to produce a high resolution texturing. We present here a static method for correcting multiple images that will be tiled on multiple meshes in order to produce a single mesh presenting multiple high resolution textures. Our method doesn't need any run time processing, and hence avoids any system's performance decrease. The main idea in our blending method is to compute on every pair of images the discontinuous line (the white line in Figures 4(a) and 4(b)) and then to merge the parts of two images around this line by applying an α-blending method.



(a) (b)

Figure 4: The white line shows the blending edge between images (a) and (b).

Seabed data is provided by an XML file registering the relationships between seabed parts and original pictures containing 3D vertices, Indexed triangles sets along with the images where these triangles are seen and also the texture coordinates of each triangle within the images (see Figure 5).

```
<texturedMesh>
  <!-- List of 3D points -->
  <point3DList>
    <point3D pt=" 34  83.51  9.9  -3.7"/>
    ...
  </point3DList>

  <!-- Triangle list of index ... -->
  <triangleList>
    <triangle    idn="0"     indice="58 60 65" currentphotographId="0">
      <photographId idn="0" name="DSC_3933.JPG"/>
      <photographId idn="8" name="DSC_3978.JPG"/>
      ...
    </triangle>
    ...
  </triangleList>
</texturedMesh>
```

Figure 5: XML file data structure

The Seabed texture building and blending is performed in two steps by exploiting the triangles/photos relationships as follows:

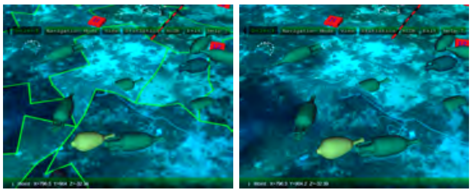
- The first step of texturing consists in choosing the best image to be used as texture for a triangle in the seabed by selecting the image where the triangle center is closer to the image center in order to avoid corners where vignetting effect occurs. We construct a new XML file that contains the list of all edges of all triangles. We also add the ID of the image used to texture the triangle and the texture coordinates in the image of the edge. Then by comparing every edges couple we parse the XML file and keep only edges presenting same vertices but two different images. After applying this parser we obtained a list of segment that define the blending edges between different images (Figure 6(a)).
- In the second step an image blending process have been carried out in order to smooth the difference of pixels' values along the edge between these images. The blending process is performed as follows: Having two images img_1, img_2 and two edges $E(A,B)$, $E'(A',B')$, where A, B, A', B' are end points of the edges in the images img_1, img_2 respectively, we blend the pixels of image img_1 around the edge E with the pixels of image img_2 around the edge E' by a linear α-blending †.

After applying this algorithm to all images, we use the images chosen in the first step to texture the seabed. The Figures 3(b) and 6(b) show the seabed before and after applying the images blending.

3. System architecture

The architecture of the VR system is composed of a database block containing all required data such as: photos, artifacts

† Something is missing in there : when and where blended image are used ?



(a) (b)

Figure 6: (a) Texture from digital seabed during processing. (b) Texture from digital seabed after image blending.

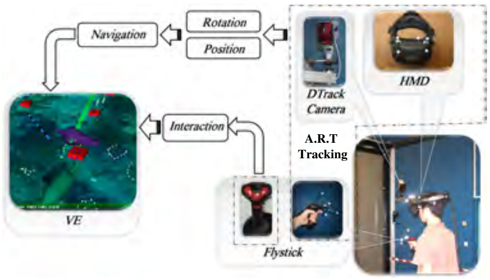


Figure 7: VE devices technology.

parameters, 2D/3D objects location, etc. The archaeological database registers the pictures taken during the survey along with 2D and 3D points of artifacts lying on the seabed measured during the photogrammetry process. When these points are labeled to belong to a recognized artifact type, an actual artifact could then be reconstructed in terms of location, orientation and size and all these parameters are also registered in the database [‡]. Therefore, such a database could be shared between the photogrammetric reconstruction process and the virtual environments designed to immersively explore the site.

In order for VE users to extract and study properties of the cargo (registered artifacts), users interaction with artifacts are translated into SQL queries to the database and results are displayed through selections or numeric data display depending on the nature of the results. Queries to the database can concern partial or complete inventory, metrology statistics (average size, similar sets,...) or spatial relationships between artifacts.

We developed 2 versions of the VR application for archaeologists which uses different devices technology. The first version works with simple input/output devices (mouse, keyboard, monitor) in order to easily run the demonstrator without having any specific devices that could be difficult to transport.

In the second version we employed more advanced devices to offer a semi or complete immersive navigation and more natural interaction with the environment. In this version we used 2 flysticks tracked by an A.R.T. cameras system that allows motion control and hence navigation, each flystick have 8 buttons and offers important number of choice to accomplish multiple tasks simultaneously. Display can be performed by a large screen with active stereo visualization or by a tracked Head Mounted Display (HMD) to increase immersion (see Figure 7 for tracked devices details).

3.1. Virtual Environment structure

All virtual environments for the VENUS project are developed around the "OpenScenegraph" high performance 3D graphics toolkit for VE modeling and visualization [BO04]. OpenSceneGraph provides high-level rendering features for 3D objects rendering, scene control and cameras views management. The main structure of the VE developed for archaeologists contains the various seabeds (large bathymetric seabed, and photogrammetric seabed with textures) and the various artifacts lying on the seabed and registered in the database. The construction of the VE is divided into 3 principal steps:

1. *Seabed:* Seabed meshes are loaded from an XML file containing 3D vertices and texture information.
2. *Artifacts:* An initial request to the database is performed to retrieve artifacts and markers parameters such as location, orientation, status, artifacts models. Then registered artifacts and markers 3D models are loaded.
3. *Virtual Environment:* These elements are placed in the virtual environment and navigation and interaction managers are started. When 3D interaction devices are available a connection to input devices is opened by using a VRPN server [TIHS*01]. The interaction manager handles inputs and eventually sends queries to the database.

4. User interface

The interface is composed of many classical tools: menu bar, information panel and popup message. The information panel displayed on the bottom of the VE (Figure 8) shows information about objects loading progress, user location or interaction result (e.g. amphora Id 21 was selected). A 3D popup message is displayed when the mouse passes over an object (or when the flystick selection ray casts an objects) showing the type of the objects or other information on selected objects.

4.1. Navigation Method

3D interactions with a Virtual environment can be divided into three principal tasks: Navigation, Selection and Manipulation. Navigation or viewpoint control is the most important task and most used when using the virtual environment. Bowman et al. [BKL05] recognized this task as the most common to all virtual environments. It allows users to explore, investigate and/or operate in a virtual space. They identified two main components for navigation: travel and way finding [BKH97], where they classified the different navigation techniques into three basic motion tasks: the

‡ A Reference to Arpenteur would be nice here

Figure 8: Tools in the Virtual Environment.

choice of direction or target, the choice of speed/acceleration of movement, and choice of entry conditions [BKL05][§].

We introduce here a new navigation technique using both hands to determine the direction of the motion and control its speed. A similar technique have been proposed by Mine et al. [MFPBS97], and is based on the knowledge of both hands position where speed is computed according to the distance between the two hands. This technique is cognitively difficult because the user may have difficulty in controlling the motion speed through the gap between his two hands. We used the angle between the hands rather then the distance which is more easy to control. The motion direction is then given by the orthogonal axis to the segment joining hands positions. Our method uses the positions and the orientations of both hands. Figure 9 shows the different parameters used to compute the direction and the speed by using two flysticks. Having positions P_1 and P_2 of the flysticks we can easily compute the motion direction $\vec{D}$ ($\vec{D} \perp \overrightarrow{P_1P_2}$). The final motion is a result of a displacement Δ along the vector $\vec{D}$ and a rotation ϕ around the center of $[\overrightarrow{P_1P_2}]$. Motion speed is inversely proportional to the angle α given by the direction of two hands whereas angle β controls rotation speed. When β reaches a $\frac{\pi}{2}$ threshold motion is turned into a pure rotation.

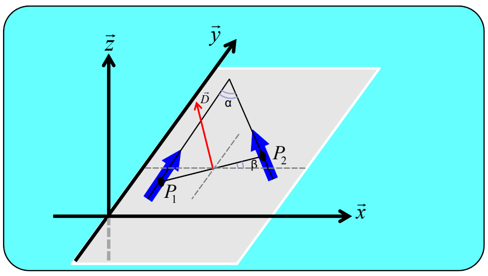


Figure 9: Navigation with two flysticks.

On the low end demonstrator navigation inside the VE is performed using a simple mouse and mouse motions effects are conditioned by the button pressed during the motion to perform translation, rotation and zoom.

§ Any comments on [BKL05] ?

4.2. Selection

Switching from navigation to selection is performed by using flysticks buttons. When the user selects an item lying on the seabed, the related informations extracted from the database are displayed on an overlay panel along with a view of the selected artefact type model. When the object is selected, the user can manipulate the item by moving it around, turning and zooming to get more details about the artifact. Several rendering techniques have been used to display amphorae according to their current status. A shaded rendering, a wire frame rendering, and a edge rendering enhancing the external boundaries of selected objects.

5. The AR demonstrator

Since archaeologists interest is mainly focused on the nature of the cargo one of the first feedbacks from archaeologists concerning VR Venus was that immersive navigation didn't provide much help to archaeological tasks in opposition to general public concerns where immersive navigation provides a deeper experience of a site. This observation lead us to propose a augmented map based navigation paradigm such as the "World in Miniature" proposed by (Stoakley et al., [SCP95]) and later applied to Augmented Reality (Bell et al. [BHF02]) which provides a much more familiar interface to archaeologists. Indeed, archaeologists have more facilities to work with maps where they can see the real world rather than a totally immersive environment in which it is difficult to be localized. Moreover, the Augmented Reality paradigm offer the opportunity to introduce a tangible interface (Ishii and Ullmer [IU97]; Poupyrev et al. [PTB*01]) to the tools developed in the VR demonstrator for archaeologists. These elements lead to the definition of a new demonstrator for archaeologists: AR Venus.

In AR Venus, archaeologists use a real map representing the deep underwater site. AR Venus proposes to enrich this environment and complete the real-world perception by adding synthetic elements to it rather than to immerse the archaeologist in a completely simulated artificial world. AR Venus provides an easy tool to interact with the real-world using tangible interface (in our case physical objects equipped with visual targets) to select and manipulate virtual objects by using a pose estimation algorithms to display artifacts models at the right location on the 2D map. Users need to wear special equipment, such as see-through head-mounted display, to see the map, augmented in real time with computer-generated features.

5.1. 3D map overlay

The first step in AR Venus is to project the 3D models of the seabed on the real 2D map using a system of visual markers identification and a pose estimation algorithm. For this visual tracking module, we used a simple webcam for tracking visual markers made up with printed 60×60 *mm* black and white fiducial. The tracking algorithm computes the real camera position and orientation relative to the physical markers in real time and also identify the content of the fiducial as a unique identifier (see Figure 10). Some fiducials are stuck on the real map in order to compute the pose of the virtual environment over the real map whereas others are use to interact.

We used OSGART library [OSG] to identify targets and overlay the 3D models on the real scene. OSGART has been designed to provide an easy bi-directional transition from VR to AR [LGSB06] by integrating ARToolkit [KBBM99] within OpenSceneGraph. The tracking library finds all squares in the binary image. For each square, the pattern inside the square is captured and matched to some pre-trained pattern templates. The square size and pattern orientation are used to compute the position of the camera relative to the physical marker, hence, the pose accuracy mostly depends on the marker size. Figure 10 shows the different steps of pose estimation algorithm (also called registration).

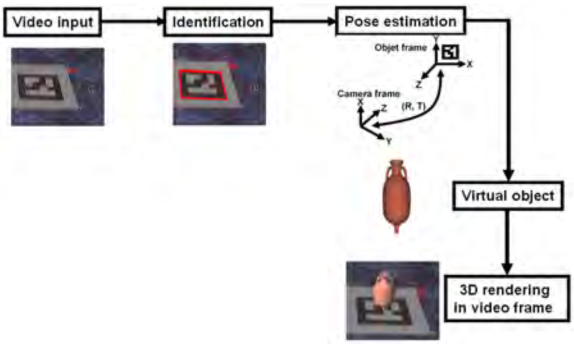


Figure 10: Pose estimation and overlay process.

5.1.1. Virtual objects registration

We used single and multiple targets with different scale to improve the tracking stability and accuracy. We started our tests using a single marker. The obtained results with a single marker were not accurate and we noticed a large shift between the virtual model and the real one represented on the 2D map. The size ratio between the small target and the large map didn't provide a correct registration, which led us after trying a larger target to consider a multitarget tracking approach since these targets are lying on the same map plane.

The multitarget approach provided a better registration along with stability improvements (also called jitter) (see Figure 11). Nevertheless, a misalignment persists as the projective transform used to print the map, has to be experimentally estimated.

5.2. Tangible interface

We saw in the previous section that static fiducials are used to register the virtual environment and artifacts, however, other targets can also be moved around the map and associated with virtual tools allowing the users to interact with the augmented environment¶.

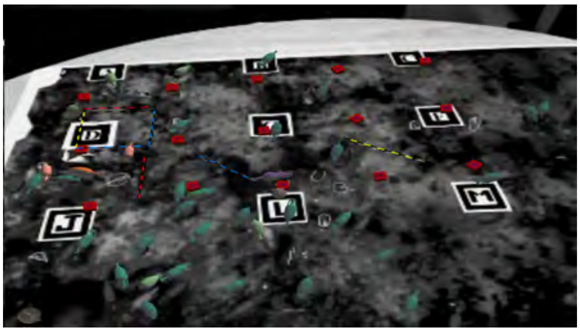


Figure 11: 3D registration using multimarker system.

We developed a working prototype with a tracking camera. Several moving targets have been associated with virtual tools such as measuring tool and inventory tool. These tools are activated whenever the camera identifies their corresponding patterns and discarded when they aren't visible anymore. Some more tools still have to be developed, however measuring and inventory tools already represent two distinct classes: the inventory tool is attached to a single target and displays the site's artifacts inventory, whereas the measuring tool displays the distance within the VE between two attached targets (see Figure 12).

Figure 12: Tangible interface of AR Venus.

We hope that archaeologists could benefit from the merging of VR/AR environments allowing easy and natural interaction with survey data registered in the artifacts database. However, these demonstrators are currently submitted to archaeologists for evaluation and feedbacks should drive the next versions of these demonstrators.

6. VR for the general public

The danger with a project such as VENUS is to generate large quantities of data that is relevant solely to archaeologists. With so many areas of expertise involved in VENUS it

¶ This part lacks some references

is not just the artifacts that are of interest. The final interface to our archaeological database is aimed at creating awareness of both the artifacts that were found and of the process with which they were discovered.

Whilst both the archaeological and general public demonstrators are based upon the same core dataset, their objectives vary greatly. Up to this point our visual interfaces have been designed for archaeologists, with an emphasis on the interaction and analysis of data. The general public, however, are less specialised in their requirements. For the general public interface, we assume that the public knows very little about the datasets and aim to provide an immersive learning experience that will supply them with information about the project data and the historical context behind it. The general public interface recreates the dive process from ship to seabed allowing members of the public to experience the exploratory process firsthand. Using a virtual environment constructed from real survey data, we allow the general public to assume the role of a virtual submarine operator tasked with uncovering the archaeological sites themselves. The vast quantity of data stored on the database enables us to create accurate three dimensional representations of the dive sites topology and then build a virtual environment around it. For the purpose of the general public interface the larger, lower resolution seabed scans are used, presenting a larger area to explore, thus enhancing the sense of discovery. The artifacts themselves are represented by three dimensional replicas, generated using the photogrammetric information on the database, positioned as found on the site (see Figure 13(a)). Giving the submarine intuitive controls is another important consideration due to varied skill sets of the general public. Thus, we allow interaction with the environment using a gamepad, more commonly seen used in conjunction with computer games consoles and a familiar interaction device to many.

Of course this data alone does not create an immersive experience. In order to promote a sense of immersion in the environment we must also reproduce the underwater conditions in which the artifacts were found. The higher density of water compared to air creates a number of lighting effects rarely seen above water. As light passes through volumes of water, it refracts, producing complex lighting effects such as 'God-rays' and caustic patterns. By combing this with environmental effects such as plants and particulate matter drifting in underwater currents we are presented with a set of powerful underwater visual cues that need to be reproduced. To replicate these effects we have created an ocean rendering engine that enables us to reproduce not only the underwater cues but also create above water ocean simulations, simulating the dive process from the very start (see Figure 13(b)).

We further enrich the dive simulation by linking it to additional textual and photographic records. As the interface gathers data directly from our archaeological database we also get access to the notes and interpretations made by archaeologists. Whilst the main goal is to provide the general public with the ability to explore the site as it was found, we also aim to highlight their historical context. Using the analysis provided by the archaeologists we are able to supply the public with background information about both the site and the artifacts. Presenting this information in a way that does not detract from the immersion within the environment is a difficult task. To achieve this we define a set of areas which represent points of interest. When a user encounters these points or looks at a particular item they are presented with a number of storyboards that appear within the heads-up display of the submarine cockpit (see Figure 13(c)). Each storyboard is fully configurable so as to provide the most recent information from the database.

7. Conclusions

All the tools presented here are still under development but represent a first step toward virtual access to deep underwater archaeological sites. Virtual and augmented reality can bring to archaeologists new insights on data gathered photogrammetric surveys concerning the seabed itself as well as the artifacts identified on the site by offering new and innovative ways to interact with these data.

We hope that by using these innovative methods of research and dissemination we can capture the imagination of the general public and generate interest not only in the historical aspect of archeology but also in the work and expertise that goes into supporting these archaeological surveys.

8. Acknowledgements

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(a) Realistic rendering of the survey site (b) Rendering of ocean surface and survey vessel (c) Example storyboarding

Figure 13: VR for the general public

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We All Live in a Virtual Submarine

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Our seas and oceans hide a plethora of archaeological sites such as ancient shipwrecks that, over time, are being destroyed through activities such as deepwater trawling and treasure hunting. In 2006, a multidisciplinary team of 11 European institutions established the Venus (*V*irtual *E*xploratio*n* of *U*nderwater *S*ites)[1] consortium to make underwater sites more accessible by generating thorough, exhaustive 3D records for virtual exploration.

Over the past three years, we surveyed several shipwrecks around Europe and investigated advanced techniques for data acquisition using both autonomous and remotely operated vehicles coupled with innovative sonar and photogrammetric equipment. Access to most underwater sites can be difficult and hazardous owing to deep waters. However, this same inhospitable environment offers extraordinary opportunities to archaeologists because darkness, low temperatures, and low oxygen rates are all favorable to preservation.

From a visualization pipeline perspective, this project had two main challenges. First, we had to gather large amounts of raw data from various sources. Then, we had to develop techniques to filter, calibrate, and map the data and then bring it all together into a single accurate visual representation.

Venus Goals and Objectives

These underwater sites are out of reach to all but a few specially trained archaeologists. Recreating the sites as interactive virtual environments lets both experts and the general public study these important pieces of (disappearing) cultural heritage in a safe, cost-effective, and pedagogical environment.

The Venus project's objectives included

- defining best practices for collecting and storing data from archaeological sites,
- surveying wrecks using remotely operated vehicles (ROVs), and
- developing software tools for visualizing, and immersively interacting with, the collected data.

To help achieve most of these objectives, the project used contemporary computer graphics and visualization techniques in various forms. For example, using an ROV to accurately survey shipwrecks can be complex and difficult for the pilot. However, through real-time visualization and tracking techniques, we can provide the pilot with a real-time 3D visualization of the ROV accurately positioned in relation to a prerendered 3D bathymetric seabed (color coded according to depth). This visualization might also include the ROV's "eyes" via a video feed from specially mounted cameras on the submersible. We can further augment the visualization to provide a "snail trail" over areas already photographed and scanned. This both facilitates identification of areas to be surveyed and identifies a possible exit route in case the ROV umbilical becomes snagged.

The project's end users are archaeologists and the general public. Here, we focus on visualization for (and dissemination to) the general public. Archaeologists aren't concerned with plant life and underwater-lighting effects; they need a clear vision of the whole site (sometimes without the seabed) and multiple interactions with the artifact. The general public, however, want to experience realistic virtual dives down to accurate visualizations of archaeological sites as though they were actually piloting the submersible.

Pianosa

Part of the project involved surveying the underwater archaeological site off the island of Pianosa, in the Tuscan archipelago. This site, discovered in 1989 by divers Giuseppe Adriani and Paolo Vaccari, is near the Scoglio della Scola (a large rock), off the island's east coast at a depth of 35 m. At the site are about 100 amphorae (ancient jars with two handles typically used to transport oil or wine) of different origins and epochs. Figure 1 shows a multibeam-sonar survey of the site.

The Pianosa survey involved significant interdisciplinary collaboration and focused on collecting georeferenced optical data for photogrammetric reconstruction. The Venus team determined an

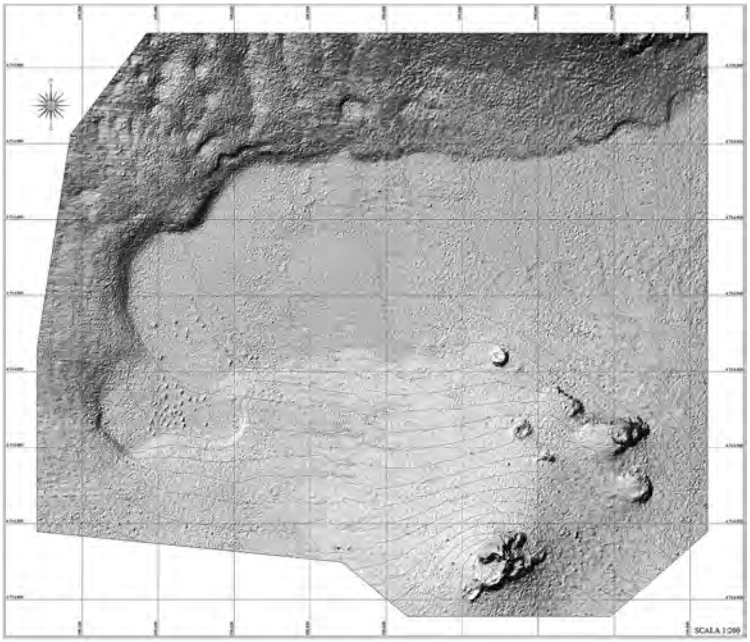

Figure 1. A multibeam-sonar image of the underwater archaeological site near the island of Pianosa, off the west coast of Italy. The site contains approximately 100 amphorae of different origins and epochs.

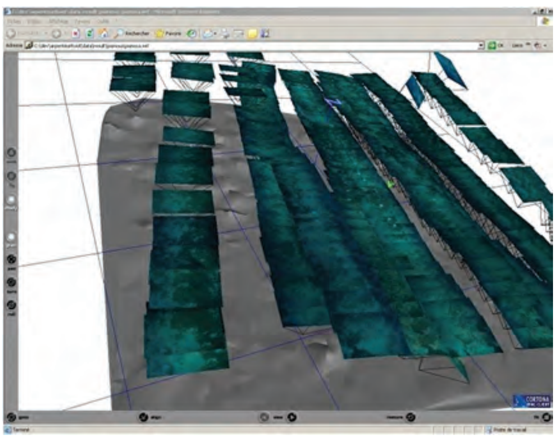

Figure 2. Oriented photographs visualized in VRML with the nontextured seabed obtained using photogrammetry. We used this unified data to create our 3D virtual environment.

area to be surveyed around the site and prepared it with 2-m scale bars and 15 cement block markers to define a control point calibration network for the ROV to measure. The data was collected by divers from the French National Centre for Scientific Research, a Venus partner, and by Integrated Systems for Marine Environment, which provided a Phantom S2 ROV for georeferencing the photogrammetric data.

Data Acquisition

We generated the photogrammetric survey using hundreds of overlapping photographs. We measured homologous points on the photographs to orient all the photographs into a local reference system. We then used the cement block positions provided by the ROV navigation data that were consistent with bathymetric-sonar data.

Figure 2 shows how we used visualization and photogrammetric tools to help unify the data sets. In this example, we used the Arpenteur photogrammetric and visualization toolbox[2] to generate and visualize a 3D model of the seabed using the corresponding overlapping and superimposed photographs. We also gathered more extensive seabed terrain data, using multibeam bathymetric sonar.

Modeling the Amphorae

The immersive visualization required 3D geometric modeling of the amphorae, which was driven by expert (archaeological) knowledge. We implemented the modeling procedure in Java and connected it to Arpenteur. The procedure is revisable over time, allowing reprocessing or augmentation as new data becomes available. We stored the resulting models in a repository database for further research and for visualization. Figure 3 shows a range of computer-generated 3D amphorae models used in the project.

The 3D Modeling Process

The process consisted of two steps: developing theoretical models and implementing a decision support system.

The theoretical models. Amphora classification in archaeology relies heavily on dimension information related to specific object features—for example, the neck. In providing a theoretical model for a specific amphora class, it makes sense to measure these features directly on actual artifacts from the site. At the Pianosa site, the divers carefully removed (and later returned) six amphorae, which we used as a paradigm to define the amphorae's theoretical models. Because these six don't account for all the classes of amphorae at the site, we complemented the direct observations of the finds with drawings and information from archival data. For example, we modeled type Gauloise 3 amphorae according to the typology presented by the University of York Archaeological Data Service (http://ads.ahds.ac.uk/catalogue/archive/amphora_ahrb_2005/details.cfm?id=135).

In defining the theoretical model, the diversity of the objects handled by the archaeologists and their surfaces' geometric complexity led us to search for stable morphological characteristics of the objects from which we could take diagnostic

Figure 3. A 3D representation of amphorae models used in the Venus project. The modeling process consisted of creating theoretical models and then implementing a decision support system that provides geometric parameters for the amphorae being studied.

measurements. To approximate these characteristics, we used a series of simple geometric primitives, which served as an interface between the photogrammetric measurements and the underlying model. For amphorae, we defined four measurement areas: rim, handle, belly, and base (see Figure 4). Using the least-square method, we fit a set of simple geometric primitives onto the measured points—for instance, a circle on the rim or belly points, or a line on the base point.

The decision support system. Photogrammetric measurements are highly incomplete (an object might be partially occluded or might have deteriorated). So, we used the Jess rule-based expert system (http://herzberg.ca.sandia.gov/jess) to determine the best strategy for providing the studied object's geometric parameters. The system started from the measurement process and handled the default data as defined in the theoretical models.

The expert system only performs geometric computation and is hidden behind the Arpenteur user interface. It's extremely useful to archaeologists because it helps fill the missing amphorae information with theoretical data. The resulting object is therefore based on a theoretical model, dimensioned by photogrammetric measurements.

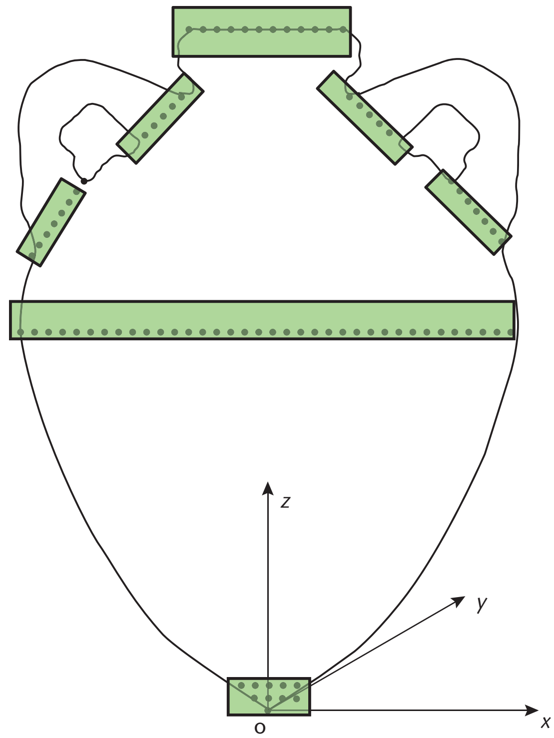

Figure 4. Potential photogrammetric-measurement locations for generating an amphora instance in the database. We defined four locations: rim, handle, belly, and base.

Working with the Models

With the Arpenteur interface, the user (generally an archaeologist) can

- recognize the amphora type in the photographs,
- choose the amphora type (see Figure 3) in the interface combo box,
- measure a set of points in the zone where measurements are allowed (see Figure 4),
- add archaeological comments and observations,
- check consistency between observations and the theoretical model, and
- store a new instance in the database.

Afterward, the user can import the amphorae database into our virtual 3D environment, which we describe later.

The Models' Usefulness

Accurate recording, modeling, and visualization of the individual amphorae provides the viewer with a first-class accurate digital reconstruction of the vessel's cargo as recorded at the time of survey. Our visualization tools have proven important for a number of tasks, such as identifying anomalies in the data. For example, because we could obtain details on demand and drill down to individual amphora data items, we could identify that one site surprisingly contained amphorae from very different epochs. Archaeologists could visualize various clusters of amphorae (in overview and zoomed-in formats) on the basis of parameters such as location, age, type, and state. So, they identified the Pianosa site as either a historical dumping ground for amphorae or a site where multiple vessels had

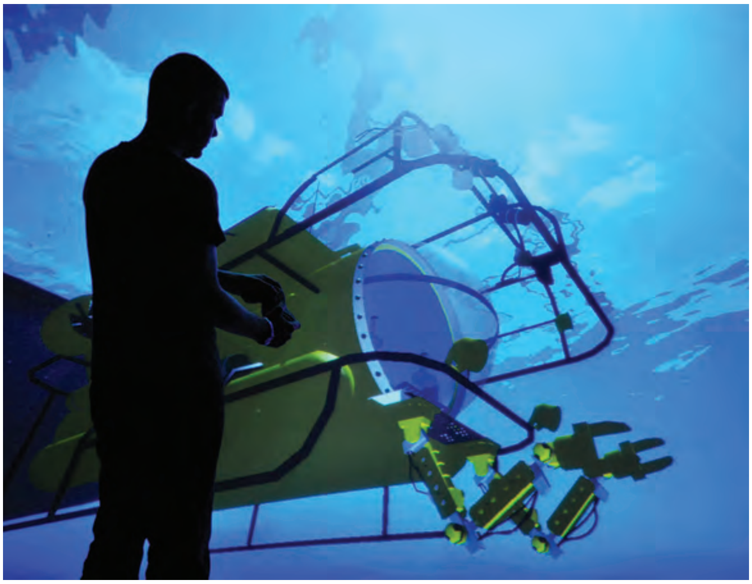

Figure 5. An archaeologist launches the virtual submarine to explore deepwater archaeological sites. After launching the submarine, the user can switch to a first-person perspective (see Figure 6).

Figure 6. Venus-PD (*V*irtual *E*xploratio*n* of *U*nderwater *S*ites-Public Demonstrator) lets the user pilot a virtual submersible down to accurate digital models of archaeological sites. This is a visualization of the Pianosa site. The shipwreck (see the inset) no longer exists; we modeled it using the recreated ship in Figure 7.

sunk (at different times), along with their cargos of amphorae.

Combining the Data

We integrated the Pianosa terrain data from the sonar bathymetry mission, the photogrammetric data for texture mapping, and the amphorae model database.[3] At this point, this data resides in a relational database. Employing a set of Java tools, we can use this data to wrap objects from the database into a VRML representation or OpenSceneGraph data file.

This final output file contains a link to every amphora in the database via a PhP interface. This interface lets the user view, check, and modify the archaeological values relating to the amphorae. Of course, the user can still access all the raw data such as measuring points, photos, and photo orientation used to measure an artifact.

The precision for all the photographs was approximately 2 cm, and the relative error was less than 5 mm when the signal was good. The absolute accuracy was approximately 40 cm (using the control points given by the acoustic measurement from the ROV).

Visualizing the Data

Scientists have successfully been using computer graphics for a number of years to improve our understanding of both offshore marine activities and land-based archaeological sites.[4] However, the oil and gas industries have traditionally dominated marine visualization, focusing on activities such as pipeline operations and debris cleanup.[5] Only limited research has dealt with underwater archaeological visualization.

We developed Venus-PD, our immersive public demonstrator, to bring interactive marine visualization to underwater archaeology and visualize data collected from Pianosa and other sites to generate an accurate first-person perspective of the entire dive process. Throughout the dive experience, the user maintains full control over the virtual submarine and can manipulate it with a full six degrees of freedom, using a commercially available game controller such as the XBox 360 wireless gamepad. Figure 5 shows an archaeologist launching the virtual submersible before diving to the Pianosa site. At the touch of a button, the user can switch to the first-person perspective and experience the dive from the cockpit (see Figure 6).

Venus-PD includes a storyboard feature triggered by certain events during the dive. For example, when the user finally arrives at the Pianosa site, the screen presents the wreck's history, including a photograph of a replica of the original trading vessel (see Figure 7). This feature has been useful for explaining to the general public the site's important elements and the Venus project's significance.

We developed Venus-PD using OpenSceneGraph, an open source, high-performance 3D graphics toolkit. Significant advances in graphics card technology have permitted real-time, per-pixel rendering of the underwater site, including

- realistic ocean surface rendering;
- depth of field and fogging (used for increased depth perception);
- silt effects;
- lighting effects (replicating the absorption and scattering of light rays as they travel through the water column onto the seabed); and
- underwater biological life, including fish and plants.

These special effects increase the pilot's sense of immersion and the virtual Pianosa site's authenticity. Consequently, when the user locates the Pianosa amphorae, he or she experiences an extremely accurate representation of the archaeological site as surveyed by the Venus team over the last three years. If the real site is ever destroyed, it's comforting to know that the 3D digital copy will continue to educate and captivate the general public.

The Venus project ended in July 2009; it resulted in a series of best practices and procedures for collecting, storing, and visualizing underwater archaeological data. Interestingly, various visualization tools developed during the project proved more successful with the general public than with the archaeologists. However, younger archaeologists (for example, PhD students) expressed real enthusiasm for these tools. A comparative study based on a questionnaire shown to 24 underwater archaeologists, along with more information and free software, is available at www.venus-project.eu.

Acknowledgments

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Figure 7. A recreated vessel similar to the Pianosa wreck. This vessel formed the basis for the shipwreck depicted in the inset in Figure 6.

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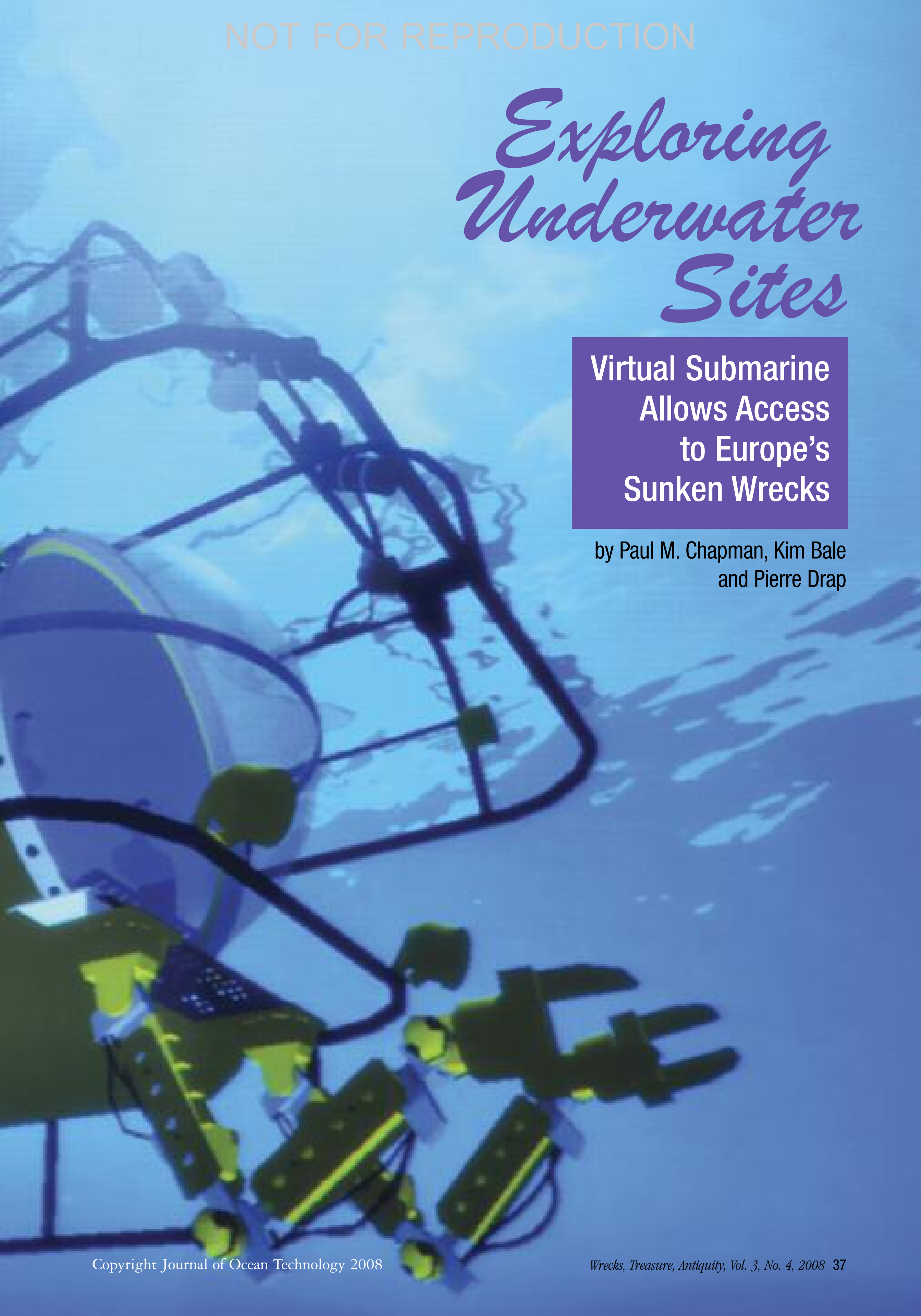

Exploring Underwater Sites

Virtual Submarine Allows Access to Europe's Sunken Wrecks

by Paul M. Chapman, Kim Bale and Pierre Drap

Computer graphics have been used successfully for a number of years to help improve our understanding of both offshore activities and land based archaeological sites. 'Marine visualization' has traditionally been dominated by the oil and gas industries, focusing on activities such as pipeline and debris clear-up operations, with limited work on shipwreck visualization. Previous work by the authors relating to shipwreck visualization has focused on relatively modern vessels such as the SS Richard Montgomery*, which sank in Sheerness, UK, August 1944. This article introduces the reader to the VENUS project (Virtual ExploratioN of Underwater Sites), a multidisciplinary project funded by the European Commission that focuses on procedures for surveying and visualizing maritime archaeological sites.*

The VENUS project aims to provide accurate three-dimensional immersive reconstructions of underwater archaeological sites providing virtual access to all. Valuable submerged archaeological sites such as shipwrecks are continually jeopardized by activities such as trawling that destroy the crucial surface layer of the site. The preservation of these wrecks, through the generation of thorough and exhaustive 3D records, is therefore of the utmost importance. At present, these sites are out of reach to all but a few specially trained archaeologists. By recreating the sites as interactive computer generated virtual environments, we permit both experts and the general public to study these important pieces of cultural heritage in a safe, cost-effective and pedagogical (learning) environment.

VENUS is composed of five objectives:

- Defining a series of best practices and procedures for collecting and storing data from the underwater archaeological site in an efficient, economic and safe manner;
- The survey of wrecks (at various depths) using autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs) and various techniques of data acquisition (sonar + photogrammetry);
- The provision of software tools (to archaeologists) for signal, data and information processing and management. These tools will allow the extraction of digital models and management of confidence levels of the collected data;
- The generation of software tools for the immersive interaction and visualization of the collected data. These tools will provide archaeologists with an improved insight into the data and the general public with simulated dives to the site;
- Disseminating the results to archaeologists and the general public via the project website (www.venus-project.eu).

Before the advent of the first civilizations in the eastern Mediterranean, the seas laid empty for millennia before becoming the main stage for the conflicts and discoveries of the ancient world. From Marathon to Lépante, from the Punic Wars to the Crusades, the Mediterranean Sea is full of historical artifacts from the dead world. Beyond its current political divisions, the Mediterranean Sea is divided into three cultural groups: the Christians, Muslims and Greek Orthodox, each of which are linked to Rome, Carthage and Constantinople. Before the advent of the first civilizations in the eastern Mediterranean, the Romans, despite imposing their will and political unification on the Mediterranean world, did not erase these cultural differences, choosing instead to use its internal seas as a gigantic trading crossroad: oils from Spain, corn from Egypt, wines from Algeria and Rhodes, slaves from Nubia, ceramics from Gallia, marble from Greece and bronze from Italy.

Amongst the varied selection of goods that travelled the Mediterranean Sea during the reign of the Roman Empire was a great quantity of Portuguese amphorae. These amphorae, used to carry the famed Lusitanian fish sauce, were shipped far and wide from the Pillars of Hercules to the Rhine frontiers.

Today, underwater archaeology provides access to Christian, Muslim and Greek Orthodox shipwrecks, complex works that testify to the wealth and diversity of past civilizations. By combining new methods of excavation, data capture and visualization, VENUS hopes to provide the opportunity for archaeologists and the

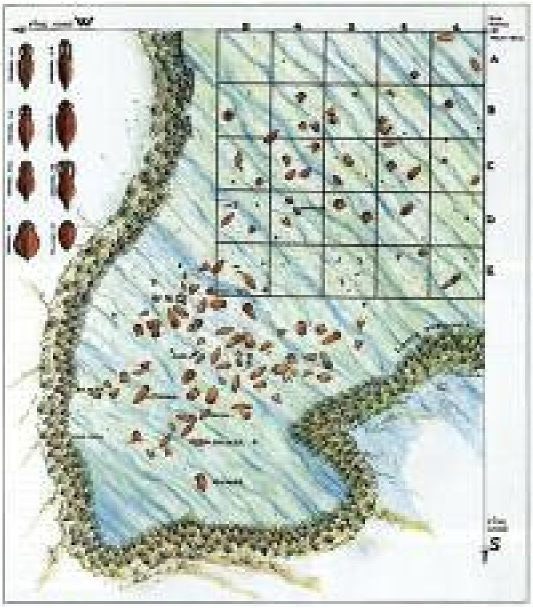

Figure 1: 1989-1991 Claudio Ruffilli's original drawing of the Pianosa site (a hand drawn survey and record of the 'Scoglio della Scola' site in Pianosa).

general public to study these sites and improve our understanding of these important trade routes for many years to come.

Case Study: Pianosa, Italy

The underwater archaeological site of Pianosa, discovered in 1989 by divers (Giuseppe Adriani and Paolo Vaccari), is located close to the Scoglio della Scola, off the east coast of the island at a depth of 35 m. The site is characterized by the presence of about one hundred amphorae of different origin and epoch. The various amphorae range from Dressel 1A (100 BC) to Beltran 2B (late middle of the second century) and Dressel 20 (late first to the early third century AD) and include some African amphorae. The site was surveyed in 2001 by the Nucleo Operativo Subacqueo (MIBAC-SBAT) divers. This survey concluded that the site had remained completely intact and undamaged and was the first archaeological site to be surveyed by the VENUS consortium.

As the depth of the site (35 m) did not allow for divers to be submerged for long periods of time, robotic equipment such as ROVs with sonar transducers and optical cameras were used to survey the majority of the site.

Figure 1 shows the pre-existing site documentation that was available to the VENUS research team. This excellent drawing by Claudio Ruffilli is typical of archaeological documentation for both marine and land based archaeological sites.

The Pianosa survey involved a significant interdisciplinary collaboration and focused on the collection of geo-referenced optical data for photogrammetric reconstruction. The data collection was carried out by divers from the VENUS partner CNRS (French National Centre for Scientific Research) and by Integrated Systems for Marine Environment (ISME) which provided a ROV (Phantom S2) equipped with a high resolution underwater camera developed by another VENUS partner, COMEX (Figure 2). After a detailed sonar and photogrammetric

Figure 2: Surveying Pianosa with ROV.

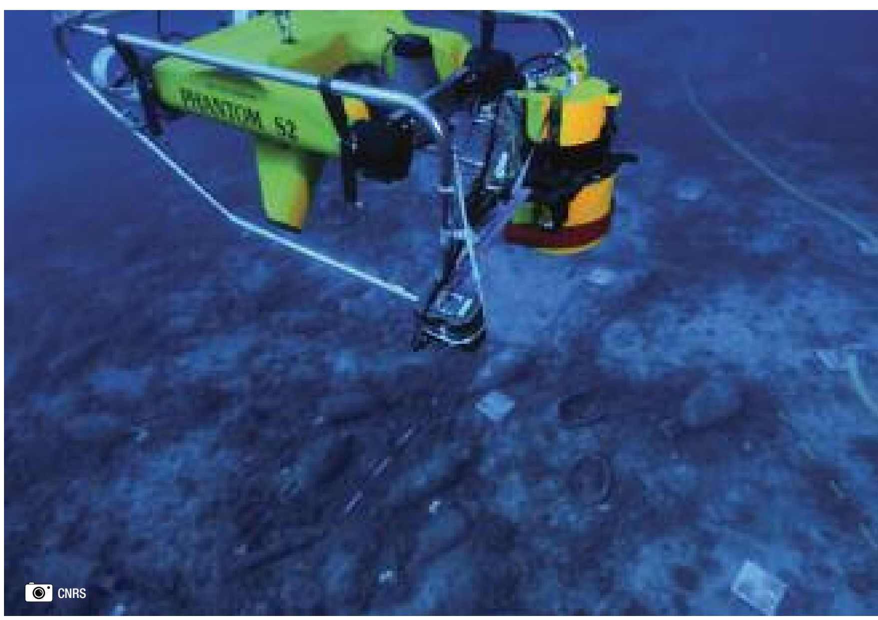


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Figure 3: VENUS-PD permits the user to take control of an underwater submersible and pilot the vessel down to accurate 3D reconstructions of archaeological sites.

The VENUS Public Demonstrator

Due to significant experience in the development of marine visualization, SimVis was tasked with managing the virtual reality public demonstrator (VENUS-PD). The goal of this simulator was to take data collected from the Pianosa survey (bathymetric terrain data, artifact type, position, etc.) and generate an accurate first person perspective of the entire dive process, from the survey vessel down to the archaeological site of Pianosa at a depth of 35 m. Throughout the entire dive experience, the user maintains full control over the submarine and is able to manipulate the vessel with full six degrees of freedom using a commercially available game controller such as the XBox 360 wireless gamepad. Figure 3 shows Kim Bale from SimVis launching the submersible prior to the dive down to the Pianosa archaeological site. At the touch of a button he is able to switch to first person perspective to experience and control the dive from the cockpit.

survey, the processed data was then passed to the SimVis research group for visualizing in their immersive public demonstrator. Figure 2 shows a photograph of the archaeological site during the survey. Fifteen concrete markers were used as a visual guide for the ROV pilot. For a more detailed explanation of the sonar and photogrammetric process, see www.venus-project.eu.

VENUS-PD includes a storyboard feature which is triggered by certain events in the dive process. For example, when the user finally arrives at the archaeological site, a storyboard explaining the history of Pianosa is displayed including a photograph of a replica of the original trading vessel (Figure 4). This storyboard feature has turned out to be a useful technique for explaining to the general public important elements of the site and the importance of the VENUS project.

VENUS-PD was developed using OpenSceneGraph, an open source, high


PIERRE DRAP, CNRS

Figure 4: Recreated wreck similar to the Pianosa wreck (200AD). Model of Grand Ribaud F Etruscan wreck, 2000.

Figure 5: VENUS-PD approaching the Pianosa site.

performance 3D graphics toolkit (www.openscene graph.org). Significant advances in graphics card technology (driven by the games industry) have permitted real-time per-pixel rendering of the underwater site including realistic ocean surface rendering, fogging (used for increased depth perception), silt effects, lighting effects (replicating light rays as they travel through the water column onto the seabed) and underwater biological life including fish and plants. These special effects all improve the pilot's sense of immersion and improve the authenticity of the virtual Pianosa site. Consequently, when the user locates the 200AD Pianosa amphorae (Figure 5 and Figure 6), they are confronted with an extremely accurate representation of the archaeological site as surveyed by the VENUS team in December 2006. If the real site is destroyed in the future, through trawling or other activities, it is comforting to know that the 3D digital copy will remain and continue to educate and captivate members of the general public.

Although the actual vessel itself would have disintegrated hundreds of years ago, the VENUS-PD software allows the user to visualize what the wreck would have looked like shortly after sinking (Figure 1). Currently the only artifacts remaining at the Pianosa site are the amphorae cargo. Visualizing an accurate model of the original vessel provides the general public with an improved understanding of the size and shape of the original trading vessel.

The UK SimVis research team has focused on the public demonstrator and realistic rendering of the site. VENUS researchers at the University of Evry, Paris, are developing visualization tools that import the same data but have targeted archaeologists as the end users. In this instance, the user requirements for the software are very different and the focus is on gaining insight into the data from a more scientific and archaeological perspective and not generating realistic visualizations of the site.

Future Developments

The VENUS consortium has recently completed two more archaeological marine surveys. The first site, Barco da Telha, is in Sesimbra, Portugal, and lies at a depth of 55 m. The second survey is a Roman wreck, Port-Miou C, and lies at a depth of 105 m in front of the limestone coast of the Calanques, between Marseilles and Cassis. The new data collected from the Portuguese and French sites will soon be imported into VENUS-PD and permit users to explore all three of the digital copies of these fascinating underwater sites.

For more information on the VENUS project, see www.venus-project.eu.

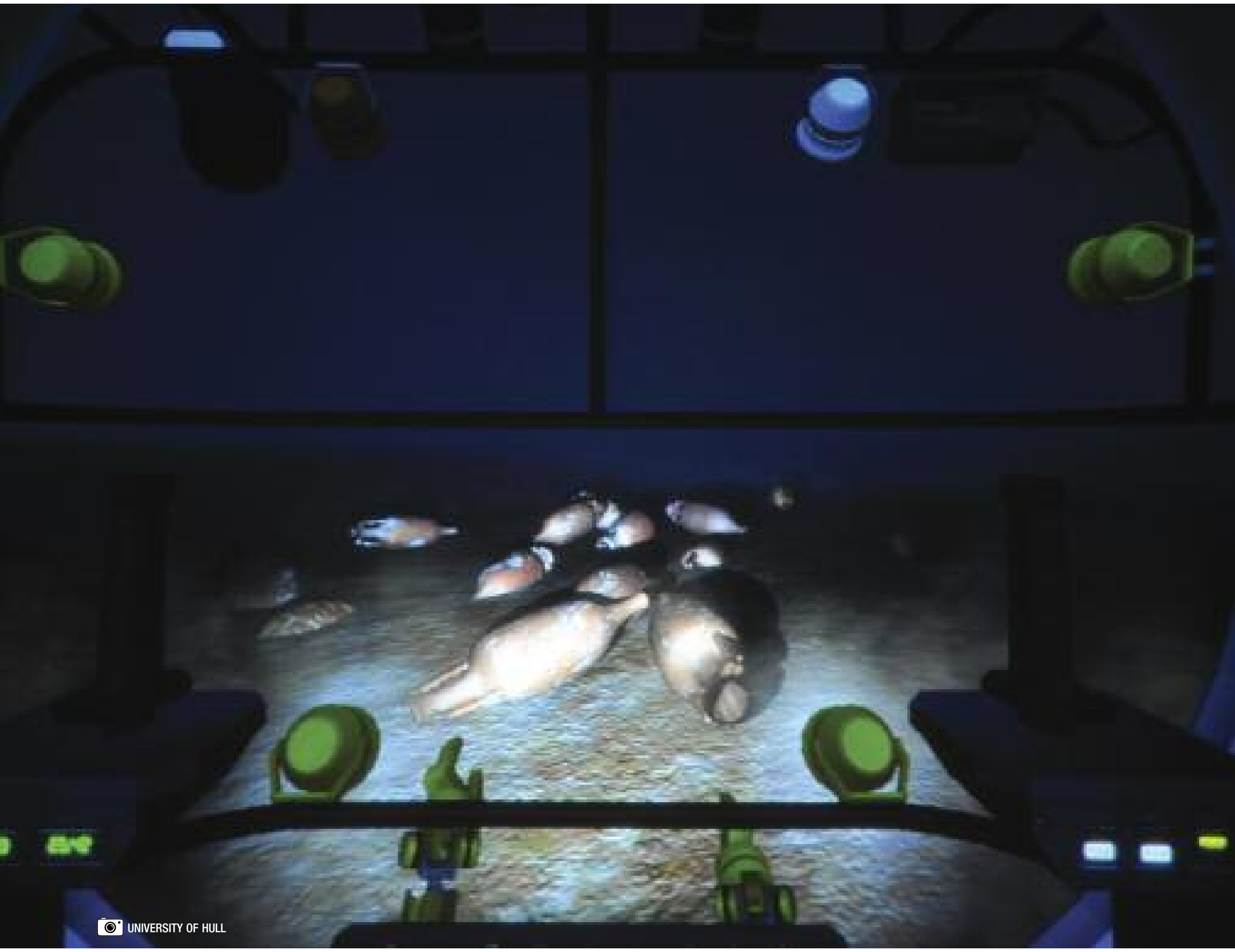

Figure 6: VENUS-PD permits the user to pilot a virtual submarine down to an accurate model of the archaeological site.

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Kim Bale is a Research Assistant based within the SimVis Research Group at The University of Hull. He holds BSc and MSc degrees in software engineering and computer graphics and is currently in the final year of his PhD investigating techniques for the visualization of multivariate time-series datasets. His recent research is focused on seabed visualization, realistic real-time rendering techniques and information visualization for medical applications.

Pierre Drap is currently Researcher in CNRS (French National Council for Scientific Research). His scientific interests are mainly concerned with close range photogrammetry and knowledge representation with a particular focus on underwater archaeology and more generally in cultural heritage.