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A Virtual Reality application for the exploration of a modern shipwreck: the case study of the Christoforos wreck

Matteo Collina[1], Antonio Lagudi [2], Fabio Bruno [2], Vincenzo Cosentino [2], Raffaele Peluso [3], Anastasios Ktistis [4], Angelos Manglis [5]

[1] *Victoria Univesity of Wellington, Museum and Heritage Studies, P.O. Box 600, 6140 Wellington, New Zealand*
[2] *University of Calabria, Department of Mechanical, Energy, and Management Engineering (DIMEG), 87036 Rende (CS), Italy*
[3] *3DResearch s.r.l., 87036 Rende (CS), Italy*
[4] *Skopelos Diving Center, Adrina beach Hotel, Panormos 370 03, Greece*
[5] *Atlantis Consulting, Λ. Κατεχάκη 17, TK 115 25, Athens, Greece*

ABSTRACT
The paper presents the development of a Virtual Reality (VR) application to perform dives in the Christoforos Shipwreck. The huge wreck lies in the Panormos Bay of Skopelos island (Greece) at a depth of 45 meters. Based on a well-known methodology designed for ancient shipwrecks, the 3D reconstruction of the underwater site has been carried out by adjusting the workflow to survey modern shipwrecks. In particular, the methodology, based on photogrammetry, is capable to provide a highly detailed 3D reconstruction of the shipwreck in a few dives, considering issues like working depth, elevations, and thin elements modelling. Moreover, the paper describes the optimization of the 3D model and the software to be executed in low-performance Head Mounted Display (HMD) devices.
The resulting VR application, realized for touristic purposes, recreates the exact ambient conditions inside and outside the water simulating the flora and fauna of the place, the coastline, allowing users to live a recreational and educational experience by virtual diving in the underwater site.

Section: RESEARCH PAPER

Keywords: virtual reality; underwater photogrammetry; modern shipwreck; cultural heritage; computer graphics technologies

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Corresponding author: Matteo Collina, e-mail: matteo.collina@vuw.ac.nz

1. INTRODUCTION

As reported by UNESCO, approximately 3 million shipwrecks lay across the oceans [1]. Ancient wrecks often provide precious historical and archaeological information, but also modern shipwrecks are important testimonies of the recent past, witnessing commercial routes, battles, and how human factors can impact the marine environment. In fact, they are good case studies to understand more about the marine life that starts growing around these artificial reefs [2]. However, corrosion and other environmental parameters strongly impact their decay [3]. Moreover, they represent a great touristic attraction for divers that enjoy this kind of underwater environment and the habitat created by these structures [4]. It is important to notice that shipwrecks usually sink at depth and for this reason are often inaccessible to most divers. In fact, while antique shipwrecks are usually located close to the coast in shallow water, allowing divers and freedivers to enjoy the real archaeological site, modern shipwrecks generally lie in deep water where the environment does not allow recreational diving. In this scenario, 3D digital technologies represent an invaluable set of effective tools for documentation and monitoring purposes [5], but also to raise awareness to the general public of these important historical and naturalistic assets [6]. Furthermore, Virtual Reality (VR) engages with the public gaining experience with emotional layers [7]. The use of 3D digital surveying and VR technologies has been already utilized for the valorization of underwater cultural heritage with reliable results [8], [9], [10]. Many archaeological sites have been already 3D reconstructed and can be experienced using VR technologies [11], [12]. For this scope, different methodologies and techniques have been developed and improved during the time [13], [14], [15].

Since those methodologies are designed to acquire shallow underwater archaeological sites, it is necessary to consider many other aspects such as working depth, organization, the complexity of the structures, and the level of detail necessary to properly present the model, when applied to a modern shipwreck.

For these reasons, 3D digital surveys of shipwrecks are usually performed with AUVs (Autonomous Underwater Vehicle) and ROVs (Remotely Operated Vehicle) [16]. This kind of approach presents the advantage of being able to capture different kinds of information such as acoustic and optical data in a single acquisition, without any limit on bottom time [17]. In contrast, it is hard to capture details and the hidden parts necessary for a virtual environment, considering the dimension and the capability of movements of the machines utilized. For these reasons, it is required to perform a close-range photogrammetry survey utilizing technical diving procedures to provide a high-quality optical 3D model to be rendered in a VR system. Moreover, the high-quality model needs to be optimized with both 3D modelling and software to be manageable for VR systems.

After a brief historical description of the site, this paper will present the workflow used to 3D reconstruct the Christoforos shipwreck through photogrammetric techniques and the optimization performed to render the model on a virtual scenario in low-cost VR HMD devices. In particular, a well-known methodology, designed for surveying ancient shipwrecks, has been customized and optimized to survey modern shipwrecks. The paper describes the survey procedures utilized while performing technical diving on modern shipwrecks, the modelling of thin elements, not-well re-constructed, based on reference images, and the software solutions adopted to render the high-detailed scene on low-performance VR hardware. Even if this shipwreck can't be considered cultural heritage, the approach and the case study represent a cost-effective business model to promote and valorize modern shipwrecks with historical value in diving centres to divers and non-divers tourists [18]. The work has been financed by the Interreg-Med 4Helix+ EU project, which aims to help small companies to implement creative projects under the guidance of Knowledge Providers experts in the Cultural and Creative industries. This voucher aimed to create a VR application to promote the underwater site during tourism fairs and diving events and to present the shipwreck to non-divers.

2. HISTORICAL CONTEXT

On the 2nd of October 1983, early in the morning, the Christoforos ship with its 15 crew members left the port of Volos for the port of Piraeus. The ship was loaded with 2.600 tons of concrete and had Algeria as the destination. The weather conditions were good but, during the evening, the wind brought rains and strong North gales. The ship had a 7 degrees angle of the list to the right which continued to increase during the time. Due to these conditions, while being 12 nautical miles north of the islet Pontiko-nisi, the ship changed the route to Panormos in Skopelos island, as suggested by the fishing vessel Giannakis. On the 2nd of October 1983, the ship arrived in Panormos, but at about 16.00 the waves broke one of the portholes of the bridge. As a result, the bridge flooded and the angle of the list on the left side increased by 17 degrees while there was an influx of water in the hold. The ballast pump and a portable one were used to pump the water without any result. At about 22.00 the angle of the ship list was so high that the right gunwale touched the water. After the captain had contacted the ship owners and the operations chamber of the Ministry of commercial shipping, he gave the order to abandon the ship, while himself, the second lieutenant, and a boatswain remained. On the 3rd of October 1983, the tries to save the ship became useless and the captain gave the crew the order to leave the ship and board on the Giannakis vessel. The Christoforos shipwreck, 80 meters long and 11 meters wide sank in an upright position at about 05.30, at a depth of 43 meters (Figure 1)[19].

(a) (b)

Figure 1. (a) The position of the shipwreck on a map (b) A recent image of the shipwreck

3. MATERIAL AND METHODS

3.1. Underwater Survey

Considering the shipwreck dimension, many things need to be addressed for acquiring proper data. First, the available budget allowed to perform no more than 4 days of diving. Moreover, considering the depth, performing more than 1 dive per day was impossible due to decompression obligations [20]. For these reasons, the dive plan was designed to properly cover the whole shipwreck structure without considering small parts and details. Those have been left to be optimized and modelled in post-production.

Bearing in mind the dangers of diving in an overhead environment, especially performing decompression dives, the time available, and the general conditions of the vessel, it was decided to not survey the inside of the shipwreck [21].

Based on these assumptions, the main diving team has been divided into two small teams composed of a camera operator and a support diver to complete the task. Also, the data acquisition has been split into two main chunks: one team worked on the hull of the shipwreck, reconstructing the vertical part, and one team worked on the bridge of the shipwreck. To connect the two acquisitions, a good overlap of the images taken was necessary, also considering the different setups of the cameras available for the teams.

Due to the hull's vertical position, applying a standard aerial photogrammetric approach to this part was impossible, so a spin-around technique has been used to cover the area (Figure 2). On the first day team n.1, with a horizontal camera position, dived around the upper part of the hull, also capturing elements of the bridge, to have enough overlap with team n.2 photographs.

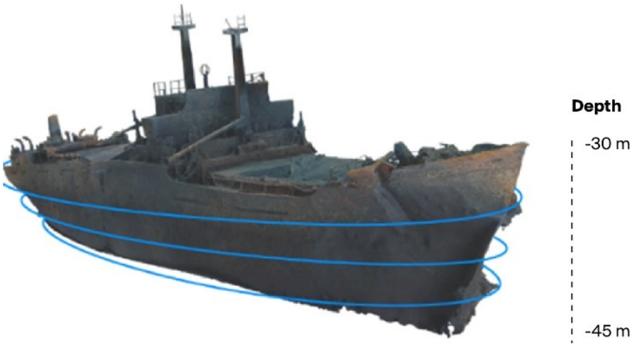

Figure 2. Representation of the path around the hull.

For the next 3 days, team n.1, with a vertical camera position, dived around the deepest part of the hull, creating strips with an overlap of 70-80%, completing 3 technical decompression dives, to collect the data of the hull and the propeller. Every dive took almost 25 minutes of bottom time and 30 minutes of decompression along the ascent using Nitrox 50% and Oxygen as decompressive gas.

To acquire the hull, team n.1 used a Sony A7II mirrorless camera with a CMOS sensor size of 36 x 24 mm and a resolution of 6000 × 4000 pixels (24 effective megapixels), equipped with a Sony Zeiss 16-35mm f/4 lens used at 16mms. The system was mounted inside an Easydive Leo3 Wi house equipped with a spherical 125 Ø port and two Easydive Revolution 15000 video lights.

Team n.2 was in charge to acquire the bridge using a standard aerial photogrammetric approach. The camera network planned to survey the site consisting of open-loop strips taken at a mean distance of 2 m above the deck, ensuring a mean Ground Sample Distance (GSD) of approximately 0.075 (cm/pixel). The camera was in a downward-looking position and was moved horizontally right–left and left–right on overlapping strips along straight lines, ensuring a 70-80% forward overlap and 50% side overlap. The occluded areas, not visible in a downward-looking position, were acquired using oblique poses. The shipwreck has been divided into 4 parts and the images produced a good amount of overlapping sequence. The work took 4 non-decompression deep dives.

To acquire the bridge, team n.2 used a Canon 5DmkIII reflex camera with a CMOS sensor size of 36 x 24 mm and a resolution of 5760 x 3840 pixels (22.1 effective megapixels), equipped with a Canon L 8-15mm f/4 lens used at 15mms. The system was mounted inside an Ikelite house equipped with a 200 Ø port and two Mangrove 5000 lumens video lights.

To properly scale and geo-referencing the model, a group of divers has taken 4 GPS points along the shipwreck deck. A diver at depth moved a reel connected to a buoy at the surface, where the GPS device was located, and have registered the depth of the point using a diving computer. A diver at the surface was responsible for taking 11 measurements from the GPS device for every point and median through measurements have been performed to reduce the error.

3.2. 3D Reconstruction

During the survey days, the 2 teams acquired 4734 pictures. To obtain the maximum level of detail all images were captured in RAW file format (.arw with Sony camera, .cr2 with Canon camera). Even with the use of the video lights, some image

(a) (b)

Figure 3. An example of an image enhancement: (a) Image before the process; (b) Image after the process.

Figure 4. The sparse cloud of the shipwreck.

processing was necessary and applied to the photos to recover the details, contrast, and colours lost at depth (Figure 3), [22].

At the end of the image processing, a typical photogrammetric pipeline has been used to 3D reconstruct the shipwreck [23]. First, a Structure-from-motion (SfM) 3D reconstruction was performed using the commercial software Agisoft Metashape Pro [24] and the measurements have been applied to the sparse point cloud resulting in an average scale error of 0.3m along with the whole shipwreck (Figure 4).

Finally, a Multi-View Stereo (MVS) algorithm was used by Metashape Pro to produce a dense 3D point cloud from the refined intrinsic orientation and ground-referenced camera exterior orientation. All the images have been used giving an output of 68.266.397 million dense point clouds (Figure 5).

Subsequently, the dense cloud has been meshed producing a 3D model of 20.000.000 polygons. As expected from the diving planning survey, thin elements have not been well reconstructed due to the low number of pictures. To recover the lost details a manual approach has been used. The model, without the texture, has been exported, and, using the pictures as a reference, the thin elements and the faint details have been modelled using the Blender software [25] (Figure 6).

Figure 5. Dense point cloud of the shipwreck.

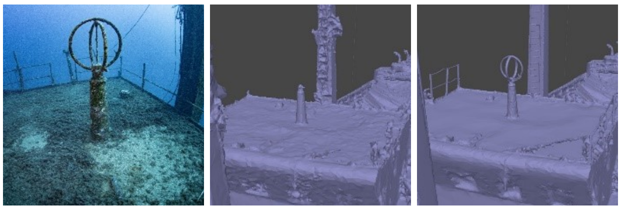

Figure 6. (a) A reference image (b) The model after the meshing processing (c) Example of modelled elements on the original mesh.

Figure 7. Final render of the shipwreck.

Later, the model has been reimported in the photogrammetric software and the texture has been projected. To avoid blue parts and equalize the texture, all the images have been masked to project only the corrected colour parts. In the end, the model has been cleaned up and corrected from the unwanted surfaces and all the holes were properly closed with Geomagic Wrap [26] and Meshlab [27] software, in preparation for use in a virtual scenario environment (Figure 7).

4. VIRTUAL SCENARIO

Once the survey and 3D reconstruction activities ended with the generation of the textured 3D model of the Christoforos shipwreck site, the 3D model has been adopted as starting point to develop an interactive virtual scenario to be exploited by users.

The HTC Oculus Quest headset has been chosen as the targeted device for the VR app for portability and costs reasons. In order to develop compatible software with this device, the Unity 3D game engine has been used for development (Figure 8).

Figure 8. A developer testing the app with an Oculus Quest device.

The creation of the scene also required a reconstruction of the seabed and the coastal surroundings of the shipwreck site, as the user exploration starts above sea level. To realize a high-fidelity representation of the Skopelos' bay, a low-resolution 3D model has been reconstructed from aerial footage [28].

At the same time, the general user experience and software have been optimized in the source code based on the available hardware. In particular, to reduce VR sickness [29] it is necessary to achieve a stable 60 FPS (Frames per Second) experience on the VR app [30]. For this reason, a series of technical issues needed to be addressed in the development stage. In fact, the most common standalone HMD devices available on market are based on Android OS and mobile hardware, implying a low Random-Access Memory (RAM) available and a low CPU and GPU throughput when compared to laptop and desktop pc specifications [31]. Moreover, it needs to be considered that the devices render the scene twice, one for each eye, doubling the processing power requirements [32].

To overcome the technical challenges faced by the app, an optimization process was implemented to reduce the polygon count of the 3D scene and minimize the number of materials utilized in the scene. This optimization process involved employing GPU and CPU optimization techniques to enhance the app's performance and usability.

The GPU optimization technique aimed to reduce the polygon count of the 3D model by removing unnecessary details and implementing more efficient algorithms for rendering the scene [33]. This approach resulted in decreased processing power requirements for rendering the scene, allowing the app to function more efficiently on devices with lower processing capabilities.

Furthermore, the CPU optimization technique focused on reducing the number of materials used in the scene, thereby minimizing the number of textures and shaders utilized. This approach optimized the CPU resource utilization for rendering the scene, resulting in improved app performance and stability.

The shipwreck 3D model, originally composed of 20 million polygons, has been simplified down to 1 million polygons by using a selective polygon decimation algorithm [34], concentrating the work on the parts of the shipwreck where there aren't particular shapes to be described (for example along the hull). Moreover, an additional gain in terms of performance has been achieved by introducing Level of Detail (LODs) logic [35]: when the camera is far from the shipwreck, it is not needed to have 1 million polygons describing it, as the underwater fog and the distance itself make it impossible to distinguish small features. Therefore, three highly decimated models of the ship are used in place of the original one, based on camera distance: a 700.000 polygons model for distances between 20 and 25 meters from the shipwreck, a 480.000 polygons model for distances between 25 and 30 meters, and a 270.000 polygon model for distances higher than 30 meters.

Concerning CPU optimization, another limitation of mobile hardware is represented by "Draw calls" [36]. CPU issues a call to GPU each time a 3D or 2D asset needs to be represented on screen (this instruction is referred to as a Draw call). Keeping the number of Draw Calls as low as possible helps to avoid bottlenecks and deliver stable performance. To achieve this, it has been necessary to reduce the number of materials used in the scene, by taking advantage of GPU Instancing [37] and Texture Atlasing techniques [38].

The exploration of the underwater shipwreck site starts above the water surface in the diving spot. To make a more attractive

Figure 9. The view from the surface at the beginning of the scene.

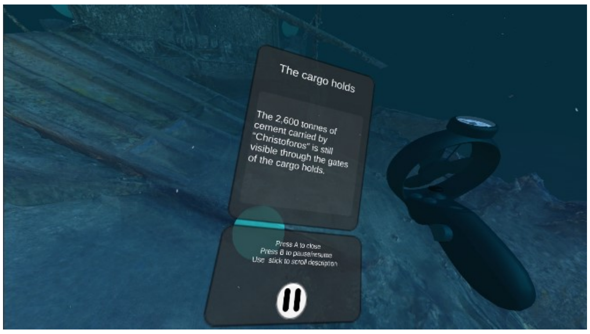

Figure 12. An activated POI along the deck of the shipwreck.

and engaging experience, the terrestrial environment has been added and constructed in the most realistic way possible. The buoy and the inflatable boat have been added to the virtual scene, as well as the 3D reconstruction of the stretch of the coastline that overlooks the diving site (Figure 9).

Achieving a realistic simulation of the underwater natural environment is critical for immersive and engaging digital experiences. To accomplish this realism, a suite of graphical effects and physically accurate simulations have been employed. These simulations include the use of light rays, which enable the app to mimic the way light behaves underwater, such as the way it scatters and reflects off surfaces. The addition of refractions, fog, caustics, particles, and bubbles also contribute to the app's overall visual realism, enabling it to create a convincing underwater environment, see (Figure 10) and (Figure 11).

Furthermore, the virtual scenario has been populated with 3D models of the flora and fauna that are typically found in the specific marine ecosystem under consideration. These models were designed to be anatomically accurate and feature realistic movement and behaviour patterns. The incorporation of such models can provide an educational component to the app, enabling users to learn more about the marine environment they are exploring.

Figure 10. Examples of the rendered light rays coming from the surface.

Figure 11. A rendered view of the stern.

Overall, the combination of graphical effects, physical simulations, and anatomically accurate 3D models contributes to a more realistic and engaging digital experience. The use of these techniques provides users with a sense of presence and immersion, enabling them to feel as though they are exploring a real underwater environment. This, in turn, can enhance the app's usability and appeal to a wider audience, including those with an interest in marine biology or environmental conservation.

During the dive, the visitor can get information about the shipwreck history and the elements on the vessel through virtual POIs (Points of Interest) [39] automatically activated when the visitor passes close to it (Figure 12).

5. CONCLUSIONS

The paper has presented the application and the adjustment of a survey methodology developed for ancient shipwrecks to a modern one. The project aimed to improve the tourist impact of the shipwreck on visitors of the Skopelos island. VR technologies are perfect for those applications thanks to their capability to allow users to explore a sensible 3D replica of the underwater site, especially in those environments where diving requires particular procedures.

Due to the elevations and the geometric characteristic of modern shipwrecks, different aspects such as survey methods, technical diving procedures, and the resulting models' complexity have been considered. In particular, the paper has described how using photogrammetric techniques in conjunction with 3D modelling can create a modern shipwreck 3D model by performing only 8 dives. To make the shipwreck more accessible to tourists, a virtual interactive scenario, optimized for standalone low-performance HMD devices, has been created. For this reason, the model has been optimized using selective polygons decimation, and software development techniques such as LODs and Draw Calls optimization have been implemented.

Furthermore, digital environments have been augmented with additional multimedia content, such as commentary, providing a more comprehensive and informative experience for the user. This multimedia content can also be used to provide educational information about the site, its historical context, and its significance, thereby adding an educational component to the user's experience.

The use of digital technologies can also provide a more accessible alternative to physical exploration of shipwrecks. For example, many shipwrecks may be located in remote or hazardous locations, making them difficult or even dangerous to access physically. By creating a digital representation, individuals who may not have the opportunity or resources to visit these sites in person can still gain a sense of their historical and cultural significance.

Overall, the use of digital technologies to create engaging representations of shipwrecks has enormous potential for the tourism sector. By providing a more accessible and immersive experience for a broader audience, digital representations can increase interest in and appreciation for these historical and cultural sites and enhance their cultural value.

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