

# 3D Reconstruction and virtual exploration of submerged structures: a case study in the underwater archaeological site of Baia (Italy)

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## Abstract

*The 3D reconstruction of underwater scenes is almost a requirement for a number of applications that need to gather 3D data from fauna, flora or submerged structures. In the Cultural Heritage field, 3D models of finds and archaeological sites are widely used, either for scientific research or for dissemination to the public. 3D imaging techniques based on multi-view capture are a valid and effective tool in underwater applications, because they require to capture the scene by different viewpoints using just one still or movie camera, installed on robots or handled by a scuba diver. In this paper we test a technique for 3D reconstructions from images captured by multiple views in a case study of submerged structures in the underwater archaeological site of Baia (Italy). This case study is particularly critical due to the high level of turbidity, the heavy presence of marine flora and the changing of lighting conditions, common in shallow water. All these disturbances cause a decrease of the contrast and an alteration of the colours in the acquired images. The 3D model of a portion of the site has been reconstructed in a virtual environment, both for studying and dissemination fruition purposes. In particular, a 3D application has been developed in order to allow the exploration of the site, the measurement of the architectural elements and the simulation of the movements of a robot that performs specific operations of restoration and preservation.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality; I.2.10 [Vision and Scene Understanding]: 3D/stereo—; J.2 [Physical Sciences and Engineering]: Archaeology—

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## 1. Introduction

Many underwater applications require to gather 3D data from flora, fauna or submerged structures, for different purposes such as monitoring, analysis, dissemination or inspection. In particular, in the Cultural Heritage field, the virtual reconstruction of submerged finds or entire archaeological sites could overcome the fact that the sites may be located in inaccessible and hostile environments, unexplorable and unknown to researchers and amateurs. Moreover, according to the guidelines of UNESCO that suggest the preservation in situ of underwater heritages [Une01], techniques and related tools for 3D reconstructions are widely employed in underwater archaeology in the last decade. Among the 3D tech-

niques suitable for underwater applications, the photogrammetry represents a valid solution to reconstruct 3D scene from a set of images taken from different viewpoints. The acquisition devices (still or movie camera with the proper waterproof housings) are very affordable and easy to use if compared to dedicated devices like LIDAR, Multi-beam, etc. and they can be installed on underwater robots or handled by scuba divers. Nevertheless, image-based acquisition suffers the critical environment conditions that may reduce the visibility and alter the colours, depending on several factors like depth, flora, weather and geographical position. These problems limit its scope of use to close range applications and require the adoption of algorithms in order to improve the image quality [SC00].

In this context, we propose to employ a photogrammetric technique based on multiple captures to reconstruct the

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3D model of submerged structures in the shallow archaeological site of Baia (Italy), a particularly interesting site because it covers a submerged area of many hectares and presents a wide range of different architectural structures, with some decorations that are still preserved. This site is the subject of study of the COMAS project [Com12] that aims to develop new methodologies and tools for conservation and restoration of submerged archaeological artifacts. Therefore, the project includes a preliminary 3D acquisition in order to document the conditions of architectural structures and to organize the subsequent operations of restoration and conservation. In fact, the structures are covered by aquatic flora and fouling organisms that rot and deteriorate the materials. The lighting conditions of the submarine environment in which the site is immersed are characterized by a high level of turbidity due to the suspended particles and the caustic effects common in shallow water (maximum depth about 14 meters). We have decided to acquire a portion of the site for a preliminary test, focusing the attention on a room of the so-called *Villa Protiro*. This case study allowed us to test 3D reconstruction algorithms from a sequence of overlapped images, widely used in air applications, in a very critical condition due to the presence of strong turbidity and various unstable elements of the scene like caustic effects, algae and fishes. Some colour correction techniques have been tested in order to enhance the contrast of the images and reproduce the true colours of the scene. Moreover, we have implemented a software application that allows the visualization and the exploration of the room in order to study and simulate the possibility to adopt a Remotely Operated Vehicle (ROV) for cleaning, restoring and maintaining the submerged structures. In particular, thanks to the simulation, we can gather useful information in order to size a robotic arm to be installed on a ROV, for removing the bio-fouling from the structures.

The paper is organized as follows. Section II presents the related works about underwater 3D reconstructions and visualization of underwater scenarios. In Section III the archaeological site of Baia is briefly described. Section IV treats about the 3D reconstruction procedure, while Section V is dedicated to 3D visualisation and interaction with a virtual environment. Finally, conclusions and future works are presented in Section VI.

## 2. Related Work

In this section, we first focus the attention on studies performed on 3D reconstruction techniques in the field of underwater archaeology; subsequently we will discuss about virtual reproduction and exploration of underwater environment.

### 2.1. Underwater 3D reconstruction

In underwater archaeology, acoustic and optical technologies are used for mapping, survey and 3D reconstruction of

finds, artifacts and submerged sites [SAFM10]. In particular, among the optical techniques available for underwater applications, photogrammetry has an important role [TF10] because of its easy applicability that requires just one or more digital cameras, also in stereo configuration. Such acquisition device can be installed on submarine robots or handled by scuba divers. Moreover, the algorithms for 3D reconstruction by photogrammetry are widely tested in air applications, and sometimes employed in water with some modifications. An underwater photogrammetric approach has been used to survey the archaeological site of Pianosa, where a Hellenistic shipwreck is present on the seabed [DSGG08, GDF11]. A series of control points are dispersed in the scene and acquired by a camera handled by a diver in order to establish the correspondence among a sequence of overlapped images. In case of deep water, like in the survey of Grand Ribaud Etruscan Wreck [DBL\*02], a diver cannot stay in water for a long time and the mapping of finds under those conditions would be almost impossible. Therefore, a light digital photogrammetry method is employed by using a non-metric digital camera, mounted in a waterproof housing attached to a bar on a submarine robot. A preliminary procedure of calibration must be performed to calculate the optical parameters of the camera and to consider the effect of refraction at the air-acrylic and acrylic-water interfaces, which are present when a camera is mounted in its housing. The refraction can be considered through the explicit modelling of the optical paths using ray tracing [LLZ\*97] or with the implicit incorporation of refraction effects into camera calibration parameters [SMG96]. In [MTJ10] a calibration method that integrates the variation of the water optical refractive index to the distortion model has been proposed for 3D underwater reconstruction of archaeological objects based on a single, uncalibrated camera. An interesting application of underwater 3D reconstructions for the Mazotos wreck by photogrammetry is proposed in [SDK12]. The images captured from a digital camera have been processed by using open source software (PMVS and Bundler). These are widely used in air for multi-view 3D reconstruction and have demonstrated their effectiveness in underwater environments if compared with a structured-light technique [BGBM11], without taking into account the optical refraction model. The site of Mazotos lies in deep water and the turbidity is very low, so factors of disturbance like turbidity, variation of the light condition, and presence of marine flora have not been considered in the experimentation.

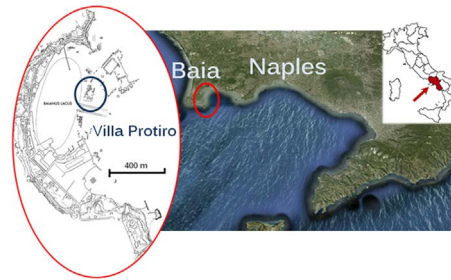
### 2.2. Virtual reality for underwater archaeology

Virtual Reality (VR) techniques have been used to make the navigation of archaeological sites easier and more intuitive [HMR\*08]. Also a 'serious gaming' philosophy has been adopted [CBD08] to create a stand-alone application for the exploration of underwater sites in a VR environment. This application also includes some technical information about the finds present on the seabed. The survey data are

integrated in a first-person view platform and visualized by the means of various VR devices with considerable results. For which concerns the on-line applications, the most used technology has been VRML [VEN12], but it could be considered an outdated technology if compared with new and more visually appealing systems. Previous works about the virtual exploration of submerged sites have been oriented to both scientific and recreational purposes [HRM\*11]. The proposed VR environment is usable both by researchers and archaeology/diving amateurs to enjoy virtual tours, either on websites or in museums and exhibitions. Nevertheless, it is also designed to allow studies that concern technical operative aspects, useful for scuba divers and ROV operators.

### 3. Archaeological context

The underwater archaeological site of Baia is located few kilometers North of Naples (Italy) (Figure 1) and belongs to the imposing volcanic complex of the Phlegrean Fields. Baia was a famous seaside town, much prized in Antiquity for its temperate climate and beautiful setting, not to mention the properties of its mineral waters which have been exploited since the 2<sup>nd</sup> century BC. It was the most popular resort of the Roman Aristocracy and the Imperial Family up to the end of the 3<sup>rd</sup> century AD, when the bradyseism caused the submersion of the city. Now the remains of villas lie underwater along the seaside, at a distance of 400-500 meters. Next to luxurious maritime villas and imperial buildings, it is possible to find more modest residences, private *thermae*, the so-called *tabernae* and all those structures that characterize the Roman age cities. In the past years, the ISCR has restored some sectors of ancient villas and structures situated in the Park of Baia with the project 'Restoring Underwater' [PM04, PD07]: the Villa con *ingresso a Protiro*, the Villa dei Pisoni, the Via Herculanea and the Edificio con cortile porticato at Portus Iulius. In particular, in the Villa con *ingresso a Protiro*, a room paved with a white mosaic and a thermal room (*calidarium*) were restored in 2003 and in 2009. The Villa con *ingresso a Protiro* is located at a depth of 5 meters; the rooms which composed the Villa are extended for 40 meters along the road, flanked by *thermae*, *tabernae* and other villas; however, its actual size must have been larger. The doorstep - framed in stucco pilasters - is delimited by two red-plastered masonry benches. The name *prothyrum* comes from the presence of two stuccoed columns shafts - no longer existing - that were placed on two short parting walls built in front of the doorstep. The floors and walls of the villa are largely decorated with marbles; almost all the surveyed rooms have marble-covered walls, and mosaic floors mostly made of white tesserae (e.g.: room no restored by ISCR in 2003). A white and black mosaic patterned with hexagons, rosette diamonds and plants - 2<sup>nd</sup> century AD - decorated a room on the North-East of the entry hall; this entry hall had a sheets wainscot in red marble of Tenario with 'Lunense' marble mouldings. The villa underwent a second construction phase represented by the build-



**Figure 1:** Geographical localization of underwater archaeological site of Baia (Italy).

ing of a wide apsidal room south of the hall. The room had two floor levels, built from large white marble sheets which were used as covers for the walls as well. The villa is also composed of other service rooms like an area identified as a kitchen in the north-western section, and a rectangular courtyard. A garden was located behind these areas: it contained the *Afrodite in Kepois* (*l'Afrodite dei giardini*) statue by Alkamenes, recovered in 1993 and now exposed in the garden of Campi Flegrei Archaeological Museum.

### 4. Image acquisition, elaboration and 3D reconstruction

As mentioned in the previous sections, the archaeological site of Baia presents several peculiarities compared to other underwater sites. In fact, we know that the Baia environment conditions, in terms of water turbidity and presence of flora, are very critical and we were not sure about the possibility to use a multi-view photogrammetric technique for obtaining a sufficiently detailed model of the structures present in the site. For this reason we decided to perform a first feasibility study in which we were going to test a 3D reconstruction technique available in literature to acquire a portion of the site elected as a case-study. Therefore, the main goal of this study was to verify if a well-known 3D reconstruction technique based on multi-view acquisition may be employed in the critical conditions of the Baia site. Other secondary goals were:

- create a first data-set that we can employ in the future for studying new techniques to monitor the changes (increasing of the bio-fouling, effectiveness of the cleaning procedures, etc.) in the preservation state of the structures;
- define a case-study to realize some simulations related to the usage of ROVs in performing cleaning and maintenance operations on the submerged structures;
- create a 3D model to be used for exploring the possibility to develop an interactive application addressed both to archaeological studies and dissemination purposes.

The room selected as a case-study is a portion of *Villa Protiro* sized 5 x 8 meters. The room is delimited by a wall with an elevation ranging around 0.5 meters. There is one

crack on the west side and it presents several blocks of bricks spread over the floor. This particular room has been selected because, at the time of the acquisition, it presented various materials (bricks, mortar, tile floors, etc.) and it was affected by a strong colonization of algae and other kind of bio-fouling, so constituting a very hard test case for the 3D acquisition techniques.

#### 4.1. Experimental setup

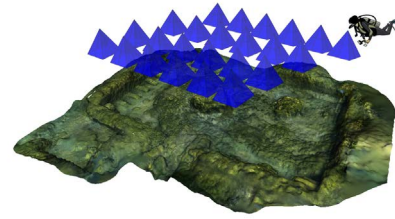
The equipment used to acquire the underwater pictures consists in a Nikon D7000 reflex camera with a 20 mm fixed lens. The camera is mounted in an underwater case manufactured by Ikelite equipped with a spherical housing. In addition two underwater strobes have been used to acquire pictures of small portions of the site that, due to the presence of shadows, were in very low lighting conditions. A second compact camera, precisely a Canon S100, mounted in a proprietary underwater housing, has been used by a second diver to record a series of full-HD videos, in order to have redundant data and reduce the risk of uncovered areas.

#### 4.2. Image acquisition

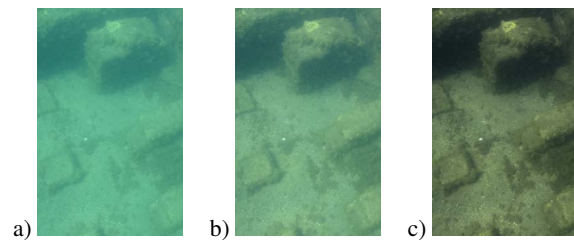
The acquisition has been carried out during two different dives, in the North section and in the South section of the submerged area. A third dive has been planned in order to complete the missed areas. The manual mode has been used during the acquisition, setting values between 1/250 and 1/320 of a second for the exposure time and an aperture between f-5.6 and f-8 to ensure a sufficient depth of field. We used the automatic ISO sensitivity function in order to ensure that the exposure was able to adapt itself to variable lighting conditions, taking advantage of the recent performance of the D7000 imaging sensor, capable of producing images with no noise even at high ISO. In order to balance the colour of underwater images, we used the pre-measured value obtained by acquiring an underwater white balance panel Lastolite. Following a standard aerial photography layout, the diver swims at a certain height/depth above the site (about 2 meter in our case) and takes overlapping pictures, ensuring about a 75% of shared coverage between two consecutive photos (Figure 2), following a straight line with constant speed in North-South direction. Several overlapping stripes have been acquired covering the whole area. Another set of stripes have been acquired in East-West direction. The occluded areas, like walls and all the features not visible in vertical pictures, have been acquired through a series of oblique photographs. About 700 images have been gathered.

#### 4.3. Colour correction

As it is well known, underwater photography is not an easy task, because the environmental conditions lead to several problems related to visibility, refraction and changing



**Figure 2:** Image acquisition using a standard aerial photography layout.



**Figure 3:** Original uncorrected image (a), acquired image using pre-measured white balance (b) and final corrected image (c).

of lighting. Underwater pictures generally suffer of light absorption, which causes some defects mostly on the red channel that is the first component of the light spectrum that is absorbed, and this effect is notable already at a depth of few meters. The pre-processing of underwater images can be conducted with two different approaches: image restoration techniques or image enhancement methods [MSP\*12, SC00]. Image restoration techniques need some known environment parameters, such as scattering and attenuation coefficients, while image enhancement methods do not require a priori knowledge of the environment. In our work, a time-saving methodology based on enhancement has been implemented through batch actions in Adobe Photoshop® to rescue the maximum amount of information from a set of defective and noisy pictures. For this purpose, a representative image of the underwater scenario has been chosen as sample in order to perform retouching and equalization, applying a four-step procedure:

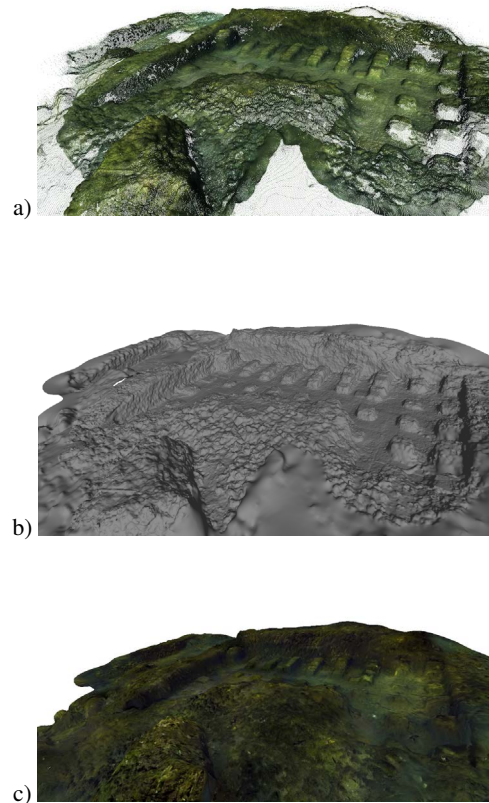
1. preliminary histogram stretching to improve the contrast;
2. mixing of the colour channels to balance the missing information on the red one;
3. creation of a set of adjustment layers on the sample image, including saturation enhancement for some missing hues, contrast masks, colour balancing and equalizing;
4. export of the statistics of the sample image on the other ones, with different mixing percentages (Figure 3).



#### 4.4. 3D reconstruction

The 3D reconstruction pipeline starts from the orientation of all the 700 selected pictures by using open source software for multi-view 3D reconstruction. We used Bundler software [SSS07] to orient the images and to retrieve the camera calibration parameters. The first phase uses the SIFT (Scale Invariant Feature Transform) to extract a set of descriptors across the collection of images that are subsequently matched. The output of Bundler consists in the intrinsic and extrinsic parameters for each camera pose and in a sparse reconstruction of the scene. The 3D reconstruction has been conducted on both original and enhanced datasets. We find that the colour correction step improves considerably the matching results. In fact, the full set of original incorrect images have not been successfully oriented, and it has been necessary to divide the dataset into two groups, for the North and South sections, to reconstruct them separately. This is mainly caused by the sandy seabed present in the central part of the room, which makes the extraction and matching of features difficult, due to the low contrast. Furthermore, the lack of overlapping areas in the reconstructed surface has prevented the alignment of the two blocks. On the contrary, the use of enhanced images allowed to orient a subset of 533 pictures related to the whole area, generating a complete 3D point cloud without the need of align different meshes. Subsequently, the Bundler's outputs and the undistorted images have been processed with PMVS2 (Patch-based Multi-View Stereo) algorithm [FP07]. This algorithm estimates the surface orientation while enforcing the local photometric consistency, which is important to obtain accurate models for low textured objects or with images affected by blur due to turbidity in underwater environment. Furthermore PMVS2 automatically reject moving objects, such as fishes and algae. The output is a dense point cloud (about 10 million points) with RGB information for each 3D point (Figure 4a). The point cloud has been processed with Meshlab tools [Mes12]. The first operation was a manual selection and deletion of unwanted areas. Then, a watertight surface with about 25 million triangles (Figure 4b) has been obtained through a Poisson Surface Reconstruction algorithm.

The resulting surface has been subsequently decimated in a mesh of 6.5 million triangles and 3 million points in order to be handled by the interactive visualization software. Since the camera orientation procedure has been carried out with an unknown scale factor, it is necessary to scale the model by selecting two points with a known distance. In our experimentation a scale bar has been placed in the scene and reconstructed in order to evaluate the scale factor. The last step consists in the application of the texture on the 3D surface. Colour information can be extracted directly from the coloured point cloud, but this method does not allow the creation of an high quality texture, because its resolution depends on the point cloud density. Since the camera positions are known, the method chosen for texture mapping consists



**Figure 4:** a) Reconstructed dense point cloud, b) resulting 3D surface, c) final textured 3D model.

into the projection and blending of the high resolution images directly on the 3D surface. In particular, we have selected an image subset because the averaging among neighbourhood values during the blending on the images works better if performed on a largely overlapped area (reducing blur effects). The result of this procedure is a texture with a resolution comparable to the original images (Figure 4c).

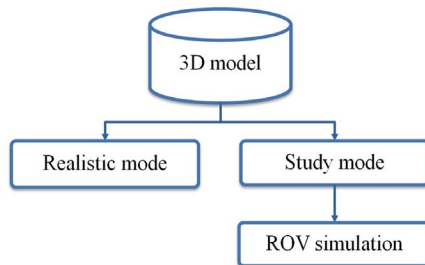
#### 5. 3D interactive environment

The 3D model of the Villa Protiro room has been used to develop an interactive application that tries to reach three different goals (Figure 5):

1. support the dissemination of the results of the COMAS project by giving the possibility to a large audience to explore a 3D underwater site reconstructed in an appealing and realistic way;
2. support the study of the archaeological site by giving the possibility to navigate in the 3D reconstruction of the room;

- support the requirement analysis for the development of a robotic arm to be mounted on a ROV specifically addressed to cleaning and maintenance operations on the underwater site.

Since the 3D environment has three different goals, the application that has been developed offers three different modes (realistic, study and simulation) characterized by different interfaces and different functionalities. The realistic mode is addressed to a general audience, the study mode is intended for archaeologists and the simulation mode has to support the collaboration between engineers and archaeologists in defining the requirements of the ROV arm. The 3D application has been developed in Virtools, a software produced by Dassault. The first step in the development of the application is to import the textured 3D model. The file format chosen for the data transfer between Meshlab and Virtools was .3ds, because this is the one that creates less conversion problems.



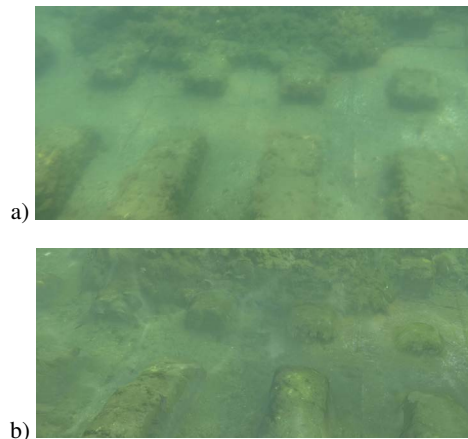
**Figure 5:** Scheme of the three applications of 3D interactive environment.

### 5.1. Realistic mode

The realistic mode makes use of some computer graphics techniques to reproduce the effects typical of a real underwater scene. As shown in Figure 6, the reconstructed environment presents no ambient light and different types of artificial spotlights, caustics effects and a strong light attenuation simulating turbidity. It is also possible to see fishes while swimming, moving fins and tail. The density of the water causes the light to be absorbed within an increasing distance, gradually preventing the visibility of the scene. In addition, the absorption of the red component of sunlight increases with the depth, flattening the shade of the surrounding colors toward green. To simulate these effects we used a virtual greenish-blue fog. Caustic effects result from light rays reflecting or refracting from a curved surface, hence focusing only in certain areas of the receiving surface. In order to simulate this effect we combined and mapped two textures on the seabed material. The first texture is obtained by the 3D reconstruction process; the second one is an image of caustics on black background.

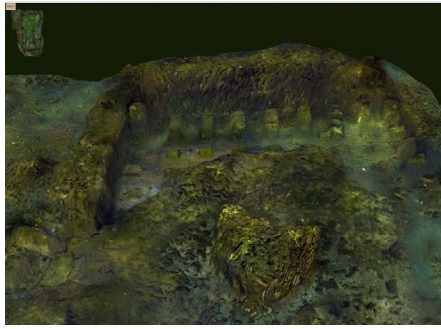


**Figure 6:** Screenshot of the application in realistic mode.



**Figure 7:** a) Photo of villa in Baia, b) Screenshot of the application in realistic mode.

The caustics motion on the seabed, due to the wavy motion of the sea surface, has been simulated using a shader (a program used primarily to calculate rendering effects on graphics hardware) that implements a sine equation. The effects of brightness, fog and caustics were calibrated manually to obtain a view as close as possible to the real one. Figure 7 illustrates a comparison between a detail of Villa Protiro room (a) and the same detail in a screenshot from the virtual application (b). The use of computer graphics techniques like fog, shaders and transparency effects increases the resource consumptions, so the user can disable them in order to speed-up the application. The realistic mode has been also transformed in a web application thanks to the Virtools web player. The web version requires a strong decimation of the 3D model in order to reduce the file size and the hardware requirements. The final version has a size of 62 Mb and requires a minimum of 3 Gb RAM and a Graphic Card with 512 Mb dedicated memory. The decimation process has reduced the number of triangles by 90% of the original 3D model, passing from 3 million vertex and 6.5 million triangles to 496.997 vertex and 613.272 triangles.



**Figure 8:** Screen-shot of the application in study mode.



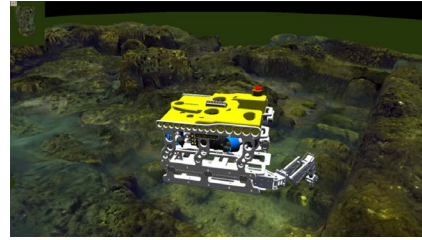
**Figure 9:** Screen-shot of the application in a top-view of study mode.

### 5.2. Study mode

For the study mode (Figure 8) we used the model with the highest quality without any decimation. The rendering does not use any visual effect for turbidity or caustics simulation and the scene is illuminated only by a strong ambient light. This kind of visualization is obviously not realistic, but it is intended to allow researchers to clearly observe and study the structures. The user can explore the site through a keyboard, a gamepad or a graphical user interface. We have decided to include a site navigation map that shows the entire exploration area and the current viewpoint position, whereas a compass clarifies the orientation of the map. Figure 9 shows the site in Top View default orientation, in which only pan and zoom actions are enabled. This default orientation includes a graduated bar as a visual reference system for distances: the bar size changes according to zoom level, allowing incremental steps for the reference unit.

### 5.3. ROV Simulation

The ROV simulation mode keeps all functionalities of study mode visualisation. Furthermore, the ROV 3D model with its own arm has been imported in the application (Figure 10); a set of additional commands is provided to move and orient the ROV and the robotic arm. The robotic arm has three degrees of freedom and it is controlled by direct kinematics,



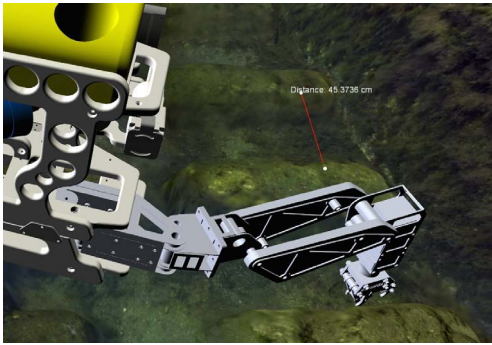
**Figure 10:** Test of reachability for narrow edges.

so the user can set the pitch and the yaw for the shoulder and the pitch for the elbow. Kinematics constraints are imposed by inserting the range of rotation for each beam. Also the collision detection between the ROV and seabed model has been implemented. Since the collision detection is a time consuming task, we implemented the possibility to set it on the whole ROV or only on a particular portion (e.g. the body, the end effector etc.). Moreover it is also possible to choose whether the contact consequences (sliding effects) have to be simulated or not. We used a Box-Face collision detection by considering only the bounding box of the ROV, whereas seabed collision surface is simulated with its own mesh. The user can also employ a tool for distance measurement (Figure 11).

## 6. Conclusions

We have presented a preliminary experimentation of 3D reconstructions in the underwater archaeological site of Baia (Italy), and the creation of a virtual scenario of a site portion for both scientific and recreational purposes. This work is part of the COMAS project that aims to develop new methodologies and tools for preservation and restoration of submerged archaeological artifacts. The lighting conditions of this site are characterized by a high level of turbidity, a heavy presence of marine flora and a continuous changing of lighting conditions, common in shallow water. A limited area of the site (Villa Protiro room) has been acquired by using open source software for multi-view 3D reconstruction. Even if these techniques have been used in other works related to underwater archaeology, our experimentation represents, in our opinion, a significant case-study to verify their robustness in presence of strong turbidity and several disturbances. We have also demonstrated that, by operating a colour correction on the image set, the results of the 3D reconstruction are improved in terms of number of points and coverage of the reconstructed area. Starting from the 3D model of the room, we have created an application that allows the visualization and the exploration of the room in order to study and simulate ROV operations of cleaning, restoring and maintaining the submerged structure. In particular, the simulation mode of the application is an useful tool to support the collaboration between engineers and archaeologists in defining the requirements of the ROV arm.





**Figure 11:** Example of reachability analysis and measuring.

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### References

- [BGBM11] BIANCO G., GALLO A., BRUNO F., MUZZUPAPPA M.: A comparison between active and passive techniques for underwater 3d applications. In *3D-ARCH 2011* (Trento, Italy, 2-4 March 2011). 2
- [CBD08] CHAPMAN P., BALE K., DRAP P.: Exploring underwater sites - virtual submarine allows access to europe's sunken wrecks. *Journal of Ocean Technology* 3, 4 (2008), 36–43. 2
- [Com12] COMAS:, accessed on September 2012. URL: <http://comas.unical.it>. 2
- [DBL\*02] DRAP P., BRUNO E., LONG L., DURAND A., GRUSSENMEYER P.: Underwater photogrammetry and xml based documentation system: The case of the 'grand ribaud f' etruscan wreck. In *ISPRS COMMISSION V SYMPOSIUM Close-Range Imaging, Long-Range Vision* (Corfu, Greece, 2-6 September 2002). 2
- [DSGG08] DRAP P., SCARADOZZI D., GAMBONI P., GAUCH F.: Underwater photogrammetry for archaeology- the venus project framework. In *GRAPP* (2008), pp. 485–491. 2
- [FP07] FURUKAWA Y., PONCE J.: Accurate, dense, and robust multi-view stereopsis. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition* (2007). 5
- [GDF11] GEORGOPOULOS A., DIAMANTI E., F.VLACHAKI: Geometric documentation of underwater archaeological sites. In *XXIIIrd International CIPA Symposium* (Prague, Czech Republic, 12-16 September 2011). 2
- [HRM\*08] HAYDAR M., MAIDI M., ROUSSEL D., MALLEM M., DRAP P., BALE K., CHAPMAN P.: Virtual exploration of underwater archaeological sites: Visualization and interaction in mixed reality environments. In *VAST International Symposium on Virtual Reality, Archaeology and Cultural Heritage and 6th Eurographics Workshop on Graphics and Cultural Heritage* (Braga, Portugal, 2008). 2
- [HRM\*11] HAYDAR M., ROUSSEL D., MAIDI M., OTMANE S., MALLEM M.: Virtual and augmented reality for cultural computing and heritage: a case study of virtual exploration of underwater archaeological sites. *Virtual Reality* 15, 4 (2011), 311–327. 3
- [LLZ\*97] LI R., LI H., ZOU W., SMITH R. G., CURRAN T. A.: Quantitative photogrammetric analysis of digital underwater video imagery. *IEEE Journal of Oceanic Engineering* 22, 2 (1997), 364–375. 2
- [Mes12] MESHLAB:, accessed on September 2012. URL: <http://meshlab.sourceforge.net/>. 5
- [MSP\*12] MAHIDDINE A., SEINTURIER J., PELOSO D., BOI J.-M., DRAP P., MERAD D.: Underwater image preprocessing for automated photogrammetry in high turbidity water. In *VSSMM2012* (Milano, Italy, 2012). 4
- [MTJ10] MELINE A., TRIBOULET J., JOUVENCEL B.: A camcorder for 3d underwater reconstruction of archeological objects. In *InOCEANS'10* (Seattle, USA, 2010), p. 109. 2
- [PD07] PETRIAGGI R., DAVIDDE B.: Restauration subaquatique: le bilan de cinq années de travaux expérimentaux de l'institut central pour la restauration. In *IVèmes Rencontres Internationales Monaco et la Méditerranée* (Monaco, France, 22-24 Mars 2007), pp. 105–116. 3
- [PM04] PETRIAGGI R., MANCINELLI R.: An experimental conservation treatment on the mosaic floor and perimeter walls of room n.1 of the so-called 'villa con ingresso a protiro' in the underwater archaeological park of baia. *Archaeologia Maritima Mediterranea* 1 (2004), 109–126. 3
- [SAFM10] SINGH H., ADAMS J., FOLEY B. P., MINDELL D.: Underwater image processing: State of the art of restoration and image enhancement methods. *EURASIP Journal on Advances in Signal Processing* 2010 (2010), 1–14. 2
- [SC00] SCHETTINI R., CORCHS S.: Imaging for underwater archaeology. *American Journal of Field Archaeology* 27, 3 (2000), 319–328. 1, 4
- [SDK12] SKARLATOSA D., DEMESTIHAB S., KIPARISSIA S.: An SopenS method for 3d modelling and mapping in underwater archaeological sites. *International Journal of Heritage in the Digital Era* 1, 1 (2012), 2–24. 2
- [SMG96] SCHEWE H., MONCREIFF E., GRUENDIG L.: Quantitative photogrammetric analysis of digital underwater video imagery. *International Archives of Photogrammetry and Remote Sensing* 31, 5 (1996), 524–529. 2
- [SSS07] SNAVELY N., SEITZ S. M., SZELISKI R.: Modeling the world from internet photo collections. *International Journal of Computer Vision* (2007). 5
- [TF10] TELEM G., FILIN S.: Photogrammetric modeling of underwater environments. *ISPRS journal of photogrammetry and remote sensing* 65, 5 (2010), 433–444. 2
- [Une01] UNESCO: Convention on the protection of the underwater cultural heritage, 2 November 2001. URL: <http://www.unesco.org>. 1
- [VEN12] VENUS V. E. O. U. S.:, accessed on September 2012. URL: <http://www.venus-project.eu>. 3