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Underwater Photogrammetry for Archaeology

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1. Introduction

Archaeological excavations are often irreversibly destructive, so it is important to accompany them with detailed documentation reflecting the accumulated knowledge of the excavation site. This documentation is usually iconographic and textual. Graphical representations of archaeological sites such as drawings, sketches, watercolors, photographs, topography, and photogrammetry are indispensable for such documentation and are an intrinsic part of an archaeological survey. However, as pointed out by Olivier Buchsenschutz in the introduction to the symposium *Images and archaeological surveys*, in Arles, France, in 2007 (Buchsenschutz, 2007, Introduction page 5), even a very precise drawing only retains certain observations that support a demonstration, just as a speech retains only some arguments, but this choice is not usually explicit. This somewhat lays the foundation of this work: a survey is both a metrics document and an interpretation of the site by archaeologist.

The survey is a very important component of this documentation and its importance is largely due to the fact that the concepts employed by archaeologists during an excavation are closely related to space. The structure of the excavation is based on the concept of stratigraphic units. Inherited from geology and then formalized for archaeology by E.-C. Harris (Harris, 1979), stratigraphic units are linked by geometric, topological and temporal relationships. They are fundamental for the interpretation of the archaeological excavation.

Two families of objects have to be surveyed: first, the artifact that we seek to position in space and of which we have a good a priori knowledge; and second, the area being excavated (in this case, a part of the seabed), often represented as a digital terrain model (DTM). Throughout this work we deal with these two aspects, artifacts and unstructured land, by addressing two different approaches; one using a priori knowledge through measurements and the second based solely on geometry.

The first approach, based on the a priori knowledge that we have about the measured artifact, uses our knowledge of the object to compute its size and position in space. This method can also reduce the time required for measurements.

The second approach, used to survey land for example, uses automatic tools coming from photogrammetry to compute a dense cloud of 3D points.

Finally, a very important point is the link between geometry and knowledge; a model, 3D or 2D, representing a site is a relevant interface to access the data known about the site. 3D representations of a site provide important added value to underwater archaeologists who are then able to study a three-dimensional overall picture, which is otherwise difficult to obtain in underwater environments. This offers a significant advantage in the creation of new assumptions regarding the reconstitution of the shipload or vessel itself (Hesnard, 1988; Long, 1995).

Moreover, it should be noted that, by nature, archaeological data are incomplete, heterogeneous, discontinuous and subject to possible updates and revisions. The documentation system, linked to archaeological data, must be able to manage these constraints.

2. Underwater photogrammetry: More than 50 years of experience

The invention of the pressure regulator (Aqua-Lung) in the 1950s enabled scuba divers to reach underwater archaeological sites and gave them the possibility of studying the wrecks of sunken ships. After the first experiments in the Fifties (of which the "excavation" of *Grand Congloué* by Jacques-Yves Cousteau and Fernand Benoit represents a milestone; celebrated, but unfit from the scientific point of view), in the Sixties archaeologists understood that they had to dive themselves to ensure that the terrestrial scientific methods used for underwater sites were correctly applied. The terrestrial methods of excavation, based on principles coming from geology and prehistoric archaeology (stratigraphic excavations), were applied by using tools adapted to the sea environment, such as suction dredgers powered by air or water, in order to remove sediment without moving the objects constituting the load of a wreck, and by excavating layer by layer the hull of the ship. On the other hand, the methods of terrestrial graphic statements (horizontal planes, vertical cuts) could not be adapted in a simple manner as they were based on optical tools, theodolites, levels, etc. Traditional methods such as tracing right angles or placing test cards on a horizontal plane were possible, but the manual graphic statement was not adaptable to the excavation of an important cargo of amphorae, ending up to be much too slow and vague without the use of a theodolite.

The first experiments of underwater photogrammetry for archaeology began in the Sixties (Bass, 1970). In the same decade, the Naval Oceanographic Office in Washington performed the first experiment with underwater photogrammetry on a submarine under the direction of Joseph Pollio (Pollio, 1968). Afterwards, other experiments took place involving the basic concepts that we use today (Ciani et al., 1971; Faig, 1979; Hoehle, 1971; Pollio, 1971). Since then, the interest in photogrammetry and acoustic measurements for archaeology has continued to grow (Bass & Rosencrantz, 1973; Tchernia et al., 1978).

In 1964, the submarine Asherah, with financial support from the National Geographic Society, was inaugurated in Turkey, and by 35 m deep took the first-ever stereoscopic photographs of the Yassi Ada 2 Byzantine wreck (Bass, 1970; Bass & Rosencrantz, 1973). A large mechanism was needed to achieve these stereoscopic images. The photogrammetric survey of a wreck in France was performed in Marseille by the French archaeologist Bernard Liou (Liou, 1973). While two synchronized cameras were taken on board the submarine Asherah, the diver in Marseille surveyed the site using fixed and sliding metal structures.

This framework was used on site to guide the cameras shooting the stereoscopic images. It was subject to strong geometric constraints; images were to be made in accordance with human physiological conditions required for stereo vision: parallel optical axes and no tipping (rotation around the optical axis).

3. Underwater survey

Studies on aboveground archaeological sites, as well as shipwreck sites, have always aimed to obtain very accurate graphical representations of reality. As soon as appropriate tools became available, a trend towards obtaining 3D representations on graphic displays also developed.

Due to their location in the open sea, where several factors such as darkness, low temperature and low oxygen rate are combined to help ensure wreck preservation, underwater sites offer extraordinary opportunities for archaeologists. However, deep wrecks are now jeopardized by an increase in deep trawling that destroys the surface layer of the sites and thus scrambles legibility. Indeed, the twenty-year-old assumption that deep wrecks would be protected from trawling is no longer true as trawl nets can nowadays be deployed down to depths of 1000 m. Therefore, many of these wrecks are likely to be destroyed even before they can be studied

The generation of thorough and exhaustive 3D records of these wrecks consequently gains importance daily. As these sites can never be experienced firsthand by the majority of archaeologists or the general public, it is very crucial to provide a faithful and accurate 3D survey of the site which can provide virtual access to all archaeological data.

3.1 Underwater 3D survey merging optic and acoustic sensors

Optic and acoustic data fusion is an extremely promising technique for mapping underwater objects that has been receiving increasing attention over the past few years (Shortis et al., 2009). Generally, bathymetry obtained using underwater sonar is performed at a certain distance from the measured object (generally the seabed) and the obtained cloud point density is rather low in comparison with the one obtained by optical means.

Since photogrammetry requires working on a large scale, it therefore makes it possible to obtain dense 3D models. The merging of photogrammetric and acoustic models is similar to the fusion of data gathered by a terrestrial laser and photogrammetry. The fusion of optical and acoustic data involves the fusion of 3D models of very different densities – a task which requires specific precautions (Drap et al., 2005; Hurtós et al., 2010).

Only a few laboratories worldwide have produced groundbreaking work on optical/acoustic data fusion in an underwater environment. See for example (Singh et al., 2000) and (Fusiello & Murino, 2004) where the authors describe the use of techniques that allow the overlaying of photo mosaics on bathymetric 3D digital terrain maps (Nicosevici et al., 2009). In this case we have important qualitative information coming from photos, but the geometric definition of the digital terrain map comes from sonar measurements.

Merging optical and acoustic survey is also done with structured light and high frequency sonar by Chris Roman and his team (Roman et al., 2010) this approach is very robust and accurate in low visibility condition but don't carry qualitative information.

3.2 Underwater photogrammetry

The principle of underwater photogrammetry does not differ from that of terrestrial or aerial photogrammetry, but it is necessary to take into account certain elements that may cause disturbance, in particular the refraction of the diopter water-glass and the presence of the housing (Butler et al., 2002).

The specific constraints of the underwater medium (turbidity of water, presence of suspended particles) force the operators to work on large scales, close to the objects (between 0.5 and 2 to 3 meters, depending on the water quality). This apparently constraining aspect imposes a great quantity of stereotypes to us, but on the other hand it offers a very high degree of accuracy.

The important advantage of using photogrammetry in underwater surveys in comparison with the use of other techniques consists in its simplicity of implementation and the diversity of potential results (3D measurements on the object, 3D reconstruction, orthophotography, and vector restitution).

The implementation only requires the use of a scale bar to compute the scale of the model. Moreover, if two or three synchronized cameras are used, additional equipment is not needed on the scene as the scale is computed using the calibration of the camera set. This approach also provides a relevant appreciation of the uncertainty of measurements; where, in addition, the photographs have to be taken with an important overlap. The key factor of this method is redundancy: each point of measured space must be seen in at least three photographs.

The operative advantage is related to the simplicity of the survey. Moreover, a submarine pilot can drive a remotely operated underwater vehicle (ROV) without having to undergo a long preliminary training period. This method requires little time and does not require specific personnel, thus greatly reducing the expenses in a context where time and costs of intervention are extremely high.

3.3 Underwater camera calibration

Camera calibration in multimedia photogrammetry is a problem that has been identified since almost 50 years ((ASP, 1980) page 838). (Bass & Rosencrantz, 1973; Fryer & Fraas, 1986). The problem has no obvious solution, since the refraction of the light beam through the different media (water, glass, and air) introduces a refraction error which is impossible to express as a function of the distortion of the image plane coordinates alone (Lavest et al., 2003). A clear presentation of this problem is related by Hans-Gerd Mass and also Mark Shortis (Maas, 2000) (Doucette et al., 2002; Shortis et al., 2007).

Telem and Finlin (Telem & Filin, 2010) propose a model which uses collinearity equations to integrate the deviation caused by refraction on a plane interface. The results are interesting but the bundle adjustment cannot be made using traditional software designed for terrestrial surveys.

Therefore the deviation due to refraction is close to that produced by radial distortion even if radial distortion and refraction are two physical phenomena of a different nature. For this reason, the approach described by Kwon (Kwon, 1998) has been adopted, consisting in the

use of standard photogrammetric calibration software to calibrate the digital cameras and their housing. This approach can indeed correct in a large part the refraction disturbance; however, it is strongly dependent on the optical characteristics of the water/glass interface of the housing. In order to minimize the refraction error due to this last interface, a housing with a hemispherical glass must be used (Telem & Filin, 2010).

3.4 Bundle adjustments

An estimation (or adjustment) technique is required when the number of available measurements is greater than that necessary to obtain a uniquely determined solution for a set of unknown parameters. From a number of estimation methods available, that of least squares is utilized most often. In many fields of science and engineering, including surveying, geodesy and photogrammetry, least-squares estimation is used extensively. (K.W. Wong, in (ASP, 1980) p. 97).

The adjustment of photogrammetric networks is accomplished via the least-squares process known as the bundle adjustment. This facilitates the simultaneous estimation of object point coordinates and image exterior orientation parameters.

The bundle adjustment incorporates various computational techniques to improve efficiency. At the same time, the goal was to make the procedure as general as possible in order to address the various requirements encountered in close range photogrammetry. These include the use of control points when available, the lack of control points (which is more typical in an underwater environment), and the implementation of constraints between points such as distance or axis constraints (Edmundson & Fraser, 1998, Edmundson, 1997).

Three dimensional network adjustment problems have an inherent rank deficiency of seven, called the network or datum defect. The datum defect exists if the network is not attached to a known coordinate system. The defect of seven includes three each for position and orientation, and one for scale.

The datum defect can be overcome by arbitrarily "fixing" the network in position, scale, and orientation through the use of control points, or points with known coordinates. The minimum number of fixed coordinates required is seven, usually obtained from two full control points and a third fixed in only one coordinate. Adjustments utilizing exactly enough constraints to define the datum are referred to as minimal constraint solutions.

Often however, particularly in terrestrial applications such as those found in archaeology or industrial photogrammetry, reliable control points are not available. Another means of eliminating the datum defect is through the inner constraints approach to free network adjustment (Blaha, 1982; Fraser, 1982).

The free network solution is optimal in that the mean variance ($\bar{\sigma}_c^2$) of the object point coordinates is minimized. In addition to its value when there are no control points, the free network is also advantageous for an accurate analysis of observation residuals. The use of redundant control can introduce stress into an adjustment which can, in turn, mask blunders that may otherwise be discovered in the residuals (Blaha, 1982).

4. Measuring artifacts, the use of archaeological knowledge

The innovative approach developed to measure in situ archaeological artifacts relates to integrating measured data with a theoretical model in order to obtain a complete representation of a partially measured object. The way to merge the different data is formalized in logical rules and for each instance measured, an expert system, fully integrated in the photogrammetric software, determines a set of operations needed for the geometrical computation.

The approach, presented in this section, was first implemented on an underwater archaeological excavation of the *Grand Ribaud F*, a deep Etruscan shipwreck discovered in 1999 in Hyères, France. The wreck is of high archaeological interest for both its cargo and its state of conservation. It is about 2,600 years old and it contains nearly 1,500 amphorae (Drap et al., 2003).

4.1 Merging theoretical model and measure

From the oriented photographs, a subsequent 3D geometrical modeling phase of the recorded artifacts (amphorae in our case) is performed. In this phase, the modeling must be driven by expert (archaeological) knowledge; thus the plotting phase is done manually, by an expert who inserts annotations to the measured geometry. The resulting models, together with the photogrammetric georeferenced data and all the survey data, are stored in a repository database for further use and interrogation.

The 3D modeling phase procedure consists in exploiting archaeological knowledge to obtain a complete representation of the measured artifacts. It is articulated in two steps:

1. **Development of the theoretical model**: for each identified object, a geometrical description offers a set of geometrical primitives, which are the only features to be potentially measured (see figure 1); these are compared with the theoretical representation of the object as derived from expert knowledge. During the site study, archaeologists have to identify amphora typologies, and a theoretical model is produced for each of them. This theoretical model is formalized in a hybrid way, using both taxonomy of archaeological artifacts and XML representation for the amphora typology.

2. **Decision Support System**: as photogrammetric measurements are highly incomplete (the object is only partially visible or may be deteriorated), a rule-based Expert System determines the best strategy to provide all the geometrical parameters of the studied object, starting from the measurement process to the handling the default data as defined in the archaeological and geometrical models. In our case, we use the Jess expert system (http://herzberg.ca.sandia.gov/jess/).

The resulting object is thus based on a theoretical model, dimensioned by a photogrammetric measurement (see figure 2, 3 and 4). The modeling procedure is revisable in time, allowing re-processing or complementary processing as new data becomes available. The whole procedure is implemented in the Java programming language and can be used with the ARPENTEUR photogrammetric toolbox (Chapman et al., 2010; Drap et al., 2003; Drap & Long, 2005; Drap et al., 2008).

Amphorae classification in archaeological work very strictly relies on dimension information for specific features of the object; for instance, the neck or belly. In providing a

theoretical model for a specific amphora class, it makes sense to measure these features directly on available archaeological finds.
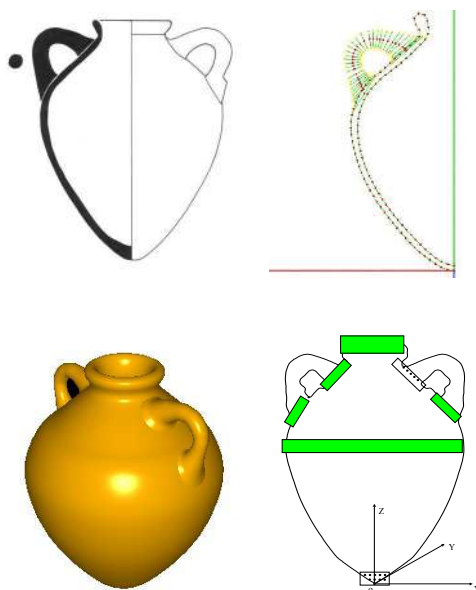

Fig. 1. On the left, the graphical model designed until now by archaeologists. On the middle two images, a CAD interpretation of this model. On the right, the five zones where photogrammetric measurements can be taken on an amphora.

In defining the theoretical model, the diversity of the objects handled by the archaeologists and the geometric complexity of their surfaces led us to search for stable morphological characteristics of the objects where diagnostic measurements could be taken. A series of simple geometric primitives are used to approximate these morphological characteristics and to act as an interface between the photogrammetric measurement and the underlying model. In the case of amphorae, four measurable zones have been defined: rims, handle, belly and bottom (see in figure 6 measured points in green on the final complete amphora model). The least-square method is used to fit a set of simple geometrical primitives onto the measured points; for instance, a circle on the rim or belly points, a line on bottom point, etc. This interface allows the user (generally an archaeologist) to

- Recognize the amphora type in the photographs;
- Choose the amphora type in the interface combo box ;
- Measure a set of points in the zone where a measurement is possible;
- Add archaeological comments and observations;
- Ensure consistency between observations and the theoretical model;
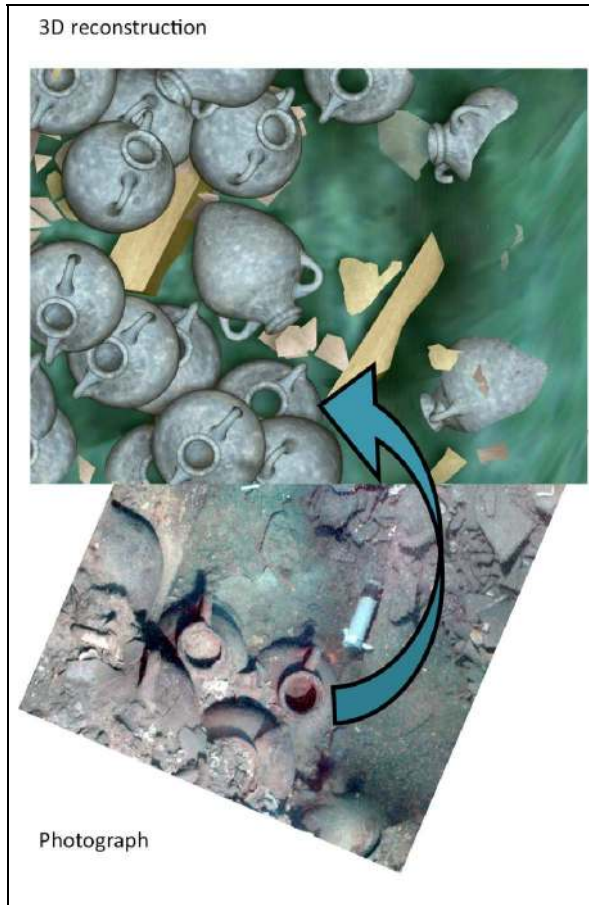- Store a new instance in the database.

Fig. 2. On the top, a complete virtual visualization of the site of the *Grand Ribaud F* wreck with all the amphorae measured. On the bottom, one of the original photographs used for the photogrammetric survey.
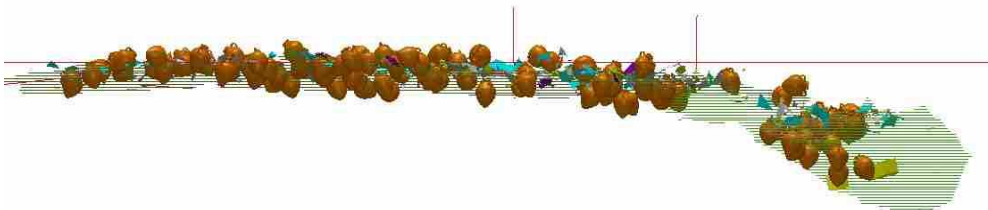

Fig. 3. An east-west elevation cut of the excavation made on the *Grand Ribaud F* wreck visualized using MicroStation™.
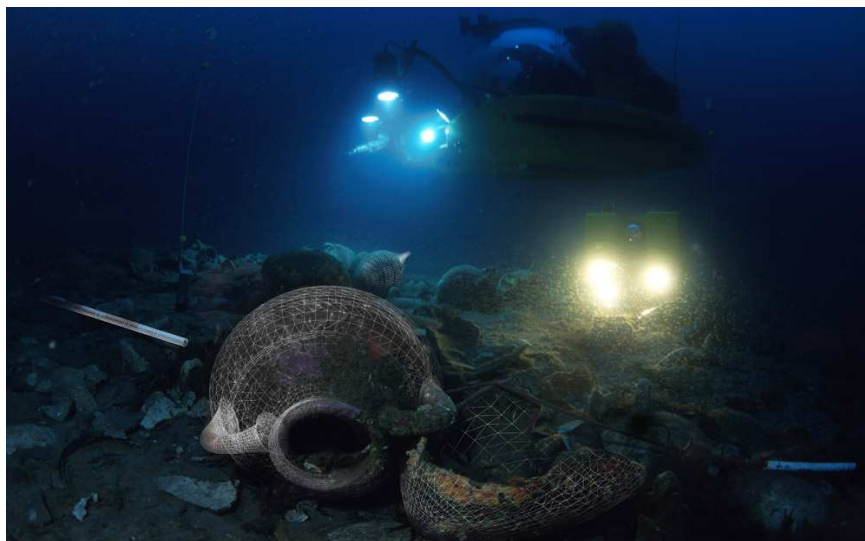
Fig. 4. The *Grand Ribaud F* wreck: a digital model of an amphora (Etruscan Py4) inserted into a photograph. (Original photograph from F. Bassemayousse).

4.2 Inconsistency check

During a survey, measurement errors can occur. The measurements of an object can be erroneous due to a poor photogrammetric restitution as it is difficult to clearly see all the objects in a photograph. For a large site survey (with large dimensions or with a large amount of objects), many surveyors can be involved in different measurement sessions. In this case, the same object may be measured more than once and different objects can be assigned the same identifier. These errors are a part of the possible errors that can occur during the construction of the final result of a survey.

For large surveys, an automatic way to ensure the consistency of a result is needed because users cannot verify by themselves all the measured objects. Such an automatic method relies on two major points:

- Verify that a set of objects is consistent
- Show inconsistent objects and origins of inconsistency to the surveyor

Using this method, the surveyor has only to correct the inconsistent objects without having to check them one by one.

The verification of the consistency is based on the knowledge of the experts in the domain. A theoretical model is constructed from expert knowledge. This model contains a description of the object (class, geometry and default values) used during the measurement sessions. From the knowledge of the experts we can also extract some constraints on the measured objects.

For example, the height h of a tile cannot exceed or be under 20% of its default value h_d. If h is the height of an amphora, the constraint can be expressed:

$$| h_d - h | < 0{,}20\, h_d$$

A constraint that involves only one object is called an intrinsic constraint. For each object typology, we have a set of intrinsic constraints given by the experts.

Constraints do not only apply to a single object. Experts can provide constraints that apply to a set of objects. Spatial constraints are a good example of constraints that involve more than one object. A spatial constraint could be the 3D representations of two amphorae that do not intersect. This constraint relies on the existence of a relation between two objects that determines if the two 3D representations intersect. Constraints that involve relations between objects are called extrinsic constraints.

The verification of the consistency of a set of objects relies on the definition of the typology of the measured objects and the set of intrinsic and extrinsic constraints. We propose a formal representation, called Entity representation, designed to verify the consistency of a set of measured objects. For more details on this approach, please refer to (Papini & Drap, 2009; Seinturier, 2007; Sérayet et al., 2011).

4.3 Accuracy

Accuracy estimation must still be improved. The first observation we can make is that the accuracy is proportional to the resolution and the scale of the photographs.

The behaviour of light underwater makes it necessary to take photographs close to the object, which ensures having a good scale. The use of a good quality digital camera with correct lighting (generally the use of a good strobe system) will ensure the best conditions to obtain good accuracy.

The general accuracy depends of two families of conditions: the geometry of the block in regards to its orientation and the way to identify homologous points on several photographs.

Regarding the geometry, it is obvious that ribbon geometry is not relevant. Overlapping between photographs and strips is important, but additional images using a smaller scale can also help fix the block orientation.

Concerning homologous point detection, a well-textured surface is important and as well as avoiding points close to the border and discontinuity. Note that automatic homologous point detection and matching using the SIFT (Lowe, 2004) or SURF (Bay et al., 2008) algorithm can be improved by image pre-processing (Kalia et al., 2011).

Nevertheless, the problem remains to quantify the accuracy. A standard estimation of variance and covariance does not seem relevant. A simple analysis of the discrepancy between the measured position and the projection of the 3D computed points onto the original photograph gives a good idea of the general accuracy of the block orientation.

If the survey is performed with only one digital camera, we need exterior information to scale the model. This can be done with a set of simple scale bars layered on the site, For example on the *Grand Ribaud F* survey, visible in Figures 2, 3 and 4, a visual verification using a 2m scale bar, not used to orient the model, gives an estimation accurate to 2mm.

In certain cases the camera can be mounted on an underwater vehicle and it is possible to benefit from the navigation data to obtain an approximation of the camera orientation and scale. Often in underwater archaeology, a survey using a multibeam sonar system is performed to obtain a small-scale representation of the site and its surroundings.

The availability of acoustic bathymetric data from the multibeam survey, which was the case in the missions organized during the VENUS (Virtual ExploratioN of Underwater Site) project (Drap et al., 2008) allows for a comparison with the final 3D model obtained with the photogrammetric approach. Nevertheless, it has to be mentioned however that the resolution of the multibeam survey is of the order of 1 sample every 0.5 m, over a large area, while the resolution of the photogrammetric data is approximately 1 sample every 0.01 m over a much smaller area. The discrepancy between the digital terrain models (DTM) obtained from the multibeam survey and the photogrammetry in the Z direction shows a mean systematic error of 0.502 m with a root mean square (RMS) of 0.073 m.

4.4 Implementation on site

The survey on the *Grand Ribaud F*, as well as on the VENUS missions presented here, was done using a single digital reflex camera, Nikon D300 or D700, and two Ikelite strobes. The camera can be mounted on an underwater vehicle or handled by a diver, as we are sure that the seabed can be represented by a DTM (no cave, no wall). We can use a set of photographs with a vertical reference to perform the survey. The photographs are taken in strips with 60% overlap for the consecutive photographs in strips with 20% overlap from one strip to another.

Using only a single camera and no acoustic survey equipment means that we do not have an *a priori* knowledge on the orientation of the photographs and we need at least a set of scale bars. Without other information, we use buoys (see Figure 5) to define a vertical axis.

Fig. 5. Buoy for vertical reference and scale bar on a wreck in Sesimbra, Portugal. 60 meters depth, photogrammetric survey by divers during the VENUS project, 2008, Photo P. Drap.

5. Cartography: GIS representation

For many years geographic information systems (GIS) have become common tools for archaeologists who see in this technology an alliance between the huge amount of information collected in the field and its graphical representation which supports the analysis. GIS graphical representations most often originate from cartography, that is to say the merging of vectors, images, and symbology using 2D visualization tools. The old culture of chart reading (see Christian Jacob's book on this subject, (Jacob, 1992)) is very useful in GIS but probably one of the obstacles in the way of a truly 3D GIS. As a matter of fact, even without realistic representation, the strength of GIS is linked to the symbolic cartographic representation of the data and offers a synthetic expression of the data analysis.

If 2D representation is sufficient to demonstrate small scale archaeological work applied to a period for which traces of the elevations do not exist, it is far from being true when one is studying a building, or in this present case, a wreck. The need for 3D representation is then of first importance and the global understanding of the study revolves around this kind of representation.

The system presented here produces 3D models of artifacts studied and their geometric patterns associated to an archaeological database (see figure 6) (Drap & Long, 2005; Drap et al., 2008).
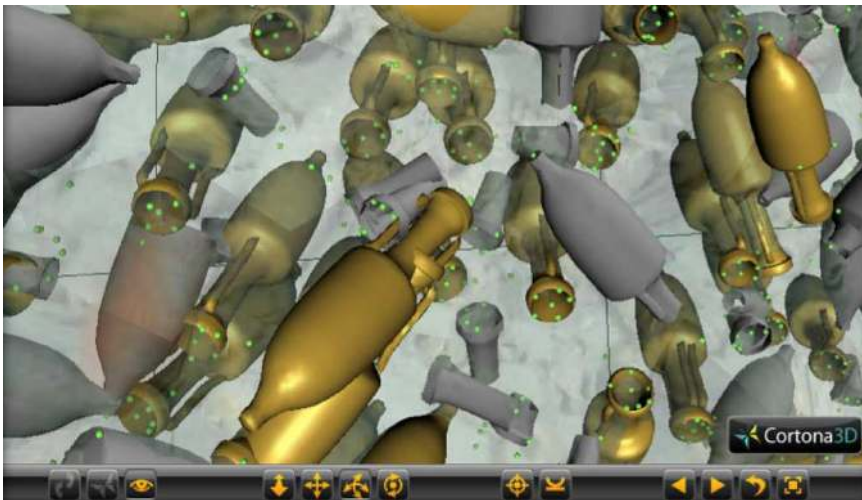
Fig. 6. 3D reconstruction of amphorae and their representation in VRML.

The link between geometry and knowledge is performed through annotations by the archaeologist and remains potentially subject to revision. The most important dimension of this work is the possible exploitation of the survey in a virtual reality system where this model interfaces with digital archaeological data. This use case may be relevant in 3D imaging, but of course also in 2D representations. In all cases, the approach is related to geographic information systems and the existing GIS standard enables the development of specific applications based on GIS concepts.

In the context of archaeological surveys, 2D representations are well known and largely used by archaeologists. These representations can be handmade drawings or digital maps as those used in computer-aided design (CAD) systems or in geographic information systems (GIS) (Peled, 2000).

The complete digital warehouse managing all the data collected on the site (all 3D information such as seabed DTM, oriented photographs, 3D artifact reconstruction, ROV navigation, etc.) allows us to automatically build a GIS representation of the surveyed site. A 2D GIS representation has two main advantages:

- The 2D representation is convenient for archaeologist needs
- A GIS enables archeologists to enhance a simple geometric representation with knowledge

As often with underwater archaeology, we are always dealing with the surface layer only, especially in deep water surveys, standard tools for terrestrial 2D GIS can be very useful.

Such a GIS representation relies on standardized formats: the GeoTIFF and the Shapefile (Shapefile is a geospatial vector file format from ESRI™ but it is an open specification and is used by numerous GIS software applications including open source projects). The Shapefile format covers simple 2D geometry representation and is suitable for a schematic representation of the measured objects. The GeoTIFF format is also able to store geo-referenced metadata of the image (see figure 14).

5.1 2D hand-drawn like representations of 3D artifacts

The generation of 2D hand-drawn like representations from 3D models is part of the wide domain of non-photorealistic rendering (NPR) of 3D models. Basically, this domain aims at providing computer techniques used to display 3D or 2D (digital images) models in artistic styles (this representation is also known as emotional design), which can be very different
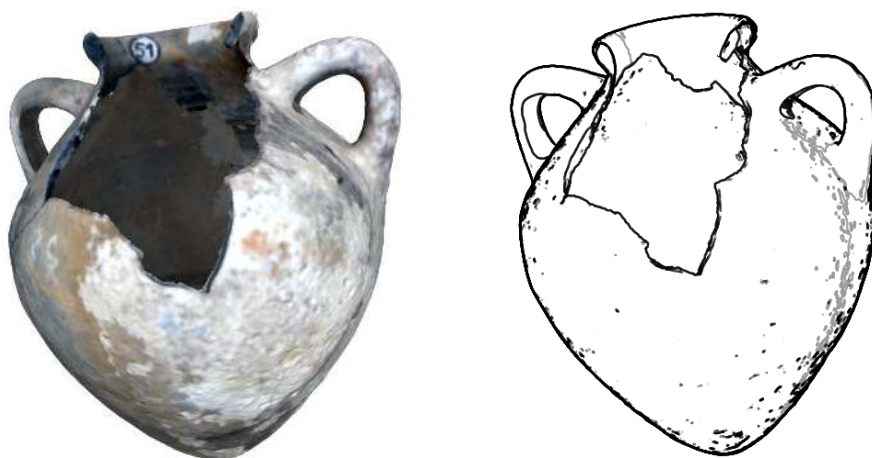

Fig. 7. An Etruscan amphora, typology Py4, from the *Grand Ribaud F* wreck. On the left, a 3D scan made in structured light using the Mephisto system. On the right, an NPR image made using the Judd algorithm (Judd et al., 2007).

from reality. See (http://www.cs.utah.edu/npr/papers.html) for a long list of papers on this topic. Several methods directly devoted or potentially applicable to the representation of 3D archaeological artifacts using NPR techniques have been discussed during the last decades. See (Jardim & De Figueiredo, 2010; Roussou & Drettakis, 2003; Tao et al., 2009) and (Judd et al., 2007) for a very interesting open source approach of NPR applied to a 3D model build with mesh and a fine implementation called *Suggestive contour software* (DeCarlo & Rusinkiewicz, 2007).

We have tested this algorithm (see figure below) on a 3D Etruscan amphora model extracted from the *Grand Ribaud F*.

5.2 2D representation generated from 3D models

The underwater sites surveyed deliver an important set of 3D data including spatial references and morphological descriptions of all the artifacts observed. These are key data for building 3D models and then 2D hand-drawn like documents, closely resembling the documents commonly used by archaeologists.

We start by an inventory of graphic conventions used in underwater archeology graphic representation by analyzing published maps.

We have identified three main rules that have guided our development:

• Only the outlines of the functional parts of the artifact (bellies, handles) are represented.
• Artifact contours are drawn from a single point of view. In other words, only the visible parts are represented.
• The round parts are highlighted by a small line drawn close to the segmented contour, and according to the point of view of the artifact's orientation.

The data required as input are:

• A set of labeled triangles: each triangle (and its respective vertices) of amphorae - or fragments - is labeled. This indicates the specific amphora zone as 'internal', 'external', 'Handle1", "Handle2", etc.
• A point of view: the point of view used to generate the 2D projection of the 3D model. In our study, we chose the projection vector (0, 0, -1), which corresponds to an orthographic view along the horizontal plane.

From these data, and of course the measured 3D points used to position and orient the amphorae in the site reference system (see figure 6, in green), we have developed a process following the three previous rules through a combination of well-known algorithms in computer graphics. This operation required several steps.

First, an algorithm designed to manage hidden lines (hidden line removal) was used to solve the problem with the global visibility of the area concerned; that is to say, certain parts should not appear depending on the point of view. It is an extension of wireframe representations.

The hidden line algorithm we developed is an adaptation of an existing algorithm (Ammeraal & Zhang, 2007). In Figure 9 this algorithm is applied to a 3D model of an amphora visible in Figure 8. After this step, we stored the data in a format able to manage the triangle data.
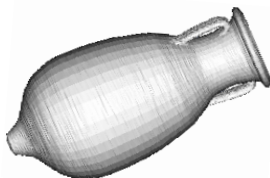
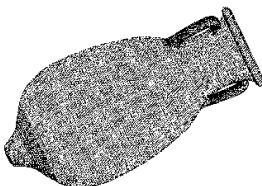Fig. 8. Triangulated model of an amphora.

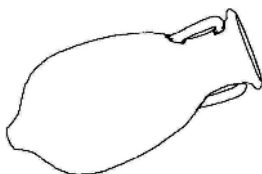Fig. 9. Hidden line removal applied to a triangulated model.

Fig. 10. Relevant lines for 2D representation.

The second step is to obtain the outline of the artifact's functional parts. This is done using the data produced by the hidden line removal algorithm. By projecting each triangle on a plane and using the Boolean union of the projected triangle according to its label, we can produce a set of shapes corresponding to the relevant part of each artifact as shown in Figure 10.

Finally we produce a set of small lines to highlight round parts of the artifact by computing the angle between the normal outline of the triangle and the projection vector, resulting in the image shown in Figure 11.
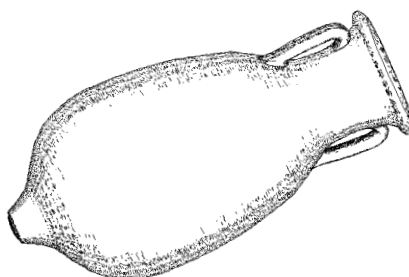
Fig. 11. Result of the hidden line algorithm rendering of the amphora shown in Figure 8.

5.3 Amphora fragments

3D amphora fragments are reconstructed by means of three types of data: a set of digitized points suitably approximating the fragment geometry, the fragment type (belly, bottom, neck) and its related amphora typology, in addition to the database of 3D amphorae constructed in the first step of the process.

From these data, a fragment reconstruction technique has been developed (see figure 12). For each fragment, the goal is to find the part of the related amphora model "suitably" corresponding to the geometrical shape of the fragment. To do this, we investigated the potential of using a matching-based technique. This is defined as the two-step process. The first step consists in fitting the fragment contour to the amphora model. The second aims at extracting the part of the amphora lying "inside" the matched contour.

3D points representing the fragment geometry are obtained using a photogrammetric interactive process, and describe the geometry of each fragment and their orientation with respect to the seabed (see figure below).
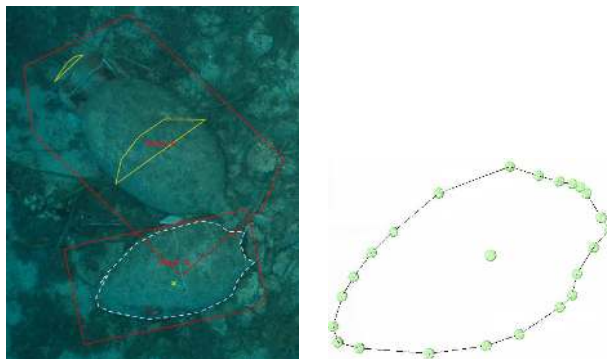

Fig. 12. On the left, the original image used to measure, by photogrammetry, the points belonging to the studied fragment. On the right, 23 points measured on the fragment's perimeter.

To obtain a satisfactory compromise between the accuracy and the size of the description while considering the potential flaws inherent to the photogrammetric interactive process, the measurement protocol we opted for was to collect for each fragment n points along its contour and one point located around its "center". This task was manually achieved by expert archaeologists using ARPENTEUR software (Drap et al., 2004). The result (for each fragment) corresponds to a 3D closed polyline, a 3D point lying "inside" the fragment, and semantic data such as the potential amphora part (e.g. a belly fragment or a handle fragment), and a potential amphora type to which the fragment may belong (see figure 12).

5.4 Matching 3D measured points on 3D amphora models

The problem of finding a satisfactory rigid registration of the measured points of a given fragment to a set of points belonging to its related amphora model has been studied as a key element for the 3D fragment generation. A formalization of the problem has led this

investigation to the theoretical problem of finding a similitude of scale 1.0, (i.e. a translation vector *t*, and a 3*3 rotation matrix *R*) in order to transform the 3D fragment perimeter into a polygonal path belonging to the amphora model.

Due to the discrete nature of the data to match, ICP-like algorithms (ICP for Iterative Closest Point), which are widely used to handle this kind of registration problem, were investigated as a potential solution. The process has been optimized by a) suitably reducing the number of points of the perimeter (reduced to 4 points for the fragment contour and an additional point for the convexity information), b) geometrically improving the way of coupling points (taking into account the angle and the length of the fragment perimeter edges for cutting the initial combinatory logic involved by the high number of data of the 3D amphora models), and c) suitably configuring the parameters controlling the minimization process (number of iterations, convergence ratio, maximum errors between the contouring points and the amphora model points).

The optimized method results in accurate matches in only a few seconds, and at the most, a few minutes. Once the five points are matched, the corresponding transformation is applied to the initial perimeter as shown in the figure below.
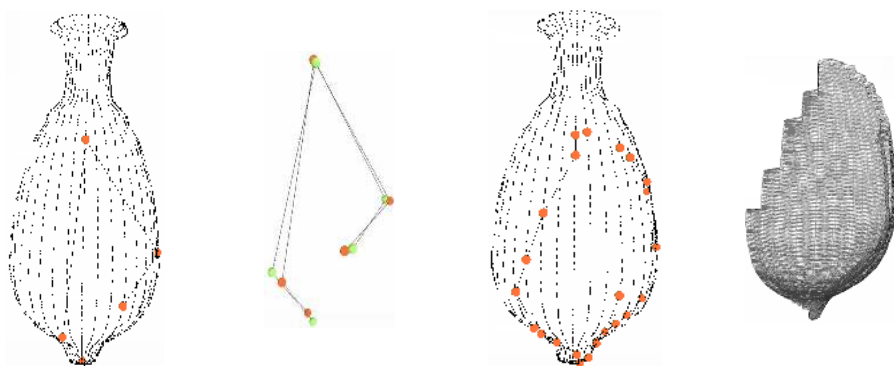

Fig. 13. Extracting triangles lying inside the matched perimeter and closing the fragment.

Fig. 14. 2D representation automatically produced using 3D simulation of a traditional archaeological drawing. Different points of view of the same artifact in 3D.
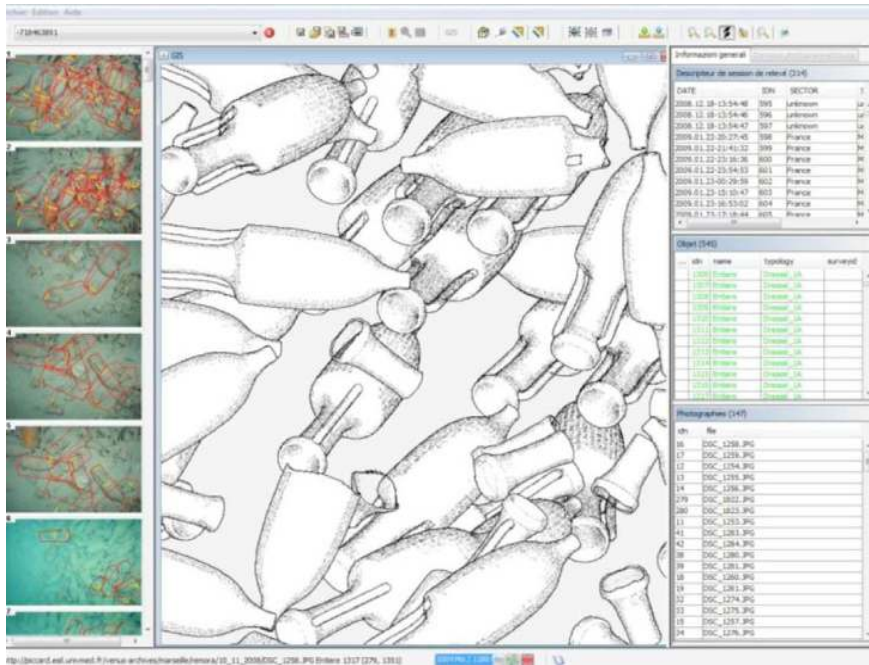
Fig. 15. 2D representation generated from the computed 3D models. The use of a standard Shapefile from ESRI™ enables interaction with archaeological data as well as photogrammetric data using standard GIS software.

6. A survey as a cloud of 3D points?

Mapping, archaeological surveys, and more generally, surveys dedicated to cultural heritage are an interpretation of the real world and not a simple exercise in data acquisition that is more or less metric.

Taking into account the interpretation of the real world during the process of archaeological surveys is similar to the work of the artist: Knowledge always guides the survey as the emotion guides the action.

New advances in photogrammetry and the capability to produce dense 3D point clouds do not solve the problem of surveys. New opportunities for 3D representation are now available and we must to use them and find new ways to link geometry and knowledge.

6.1 Automatic survey by photogrammetry

The photogrammetric process is a very efficient procedure consisting mainly in two phases. The first phase is data acquisition by photographs which requires light processing and is non-intrusive (remote sensing), not time consuming (only the time necessary to take pictures), and potentially a quite thorough practice. The second phase is further data elaboration, carried out in a laboratory. The latter phase is always manual and time consuming.

In case of photographs taken by an ROV, it is possible to minimize the time and costs of photo elaboration, taking advantage of the way underwater photographs are taken (often by strip with an overlap from one photo to the next).

Using the SIFT (Lowe, 2004; Munich et al., 2006) algorithm to detect homologous points, we will make all the possible relative orientations using the Stewenius algorithm (Kalantari et al., 2011; Nister, 2004; Stewenius et al., 2006).

Once we have automatically detected a set of homologous points on the photographs, we compute all the possible relative orientations by looking for common points between the possible pairs.

A pre-orientation computation based on the relative orientation of the common points of stereoscopic image pairs is developed, which will enable the computation of all photograph orientation data in a unique reference system.

This phase will be the key to start the bundle adjustment and compute the final external orientation necessary for the surface densification and orthophoto generation.

This task, from homologous point determination, bundle adjustment and the generation of dense point clouds is now fully automatic thanks to the work on bundle adjustment of Manolis Lourakis (Lourakis & Argyros, 2009) and Noah Snavely (Snavely et al.) for the *Bundler* software and finally Ponce and Furukawa for the point cloud generation (Agarwal et al., 2010; Furukawa & Ponce, 2008, 2010).

This software suite is now open source and freely available on the Internet.

A very interesting application is being developed by the IGN in France and offers dense 3D motion capture software which is also open source (Pierrot-Deseilligny & Cléry, 2011). Their approach is more rigorous, from a photogrammetric point of view, and allows using calibrated cameras.

This dense map approach makes it possible to obtain a dense and accurate 3D points cloud with colour information directly extracted from the photographs.

6.2 Large scale detail by photogrammetry

We also tested as part of this mission approach automatic mapping proposed by Furukawa and Ponce (Furukawa & Ponce, 2010). We tested this approach on large-scale details, Gorgonaria whose ends were slightly in motion because of the water current, see figure below.

The Gorgonaria colonies presented here is about 30 cm length and we are close to a macro scale approach.

One camera was used and sixty photographs were taken for each of the tests that follow. The study of the accuracy and the percentage of coverage were not yet completed at the time of publication due to the fact that the study dates only from April 2011.

6.3 The "Liban" wreck

The *Liban* is a ship built in 1882 in Glasgow (Scotland), measuring 91 meters long and 11 wide. It was equipped with a steam engine. On June 7, 1903 at noon, the *Liban* left the port of Marseille and less than one hour later sunk after a big collision with another ship.
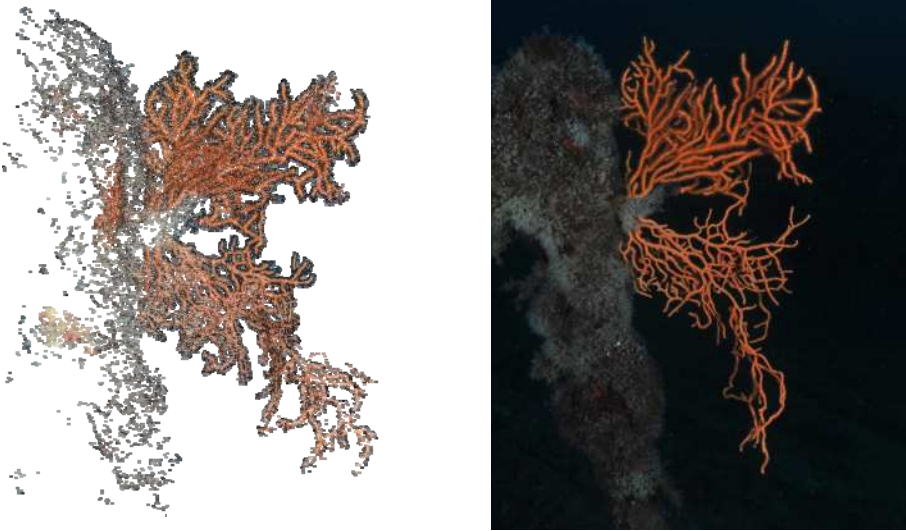
Fig. 16. On the right, one of the 64 digital photographs taken. On the left, the point cloud automatically computed using the Furukawa method.

Today, the *Liban* is a very attractive dive site close to Marseilles at 30 meters deep. We chose to survey the bow in order to develop and test our approach. Three dives and almost 2000 photos were necessary to obtain the 3D point cloud visible in Figures 17 and 18.
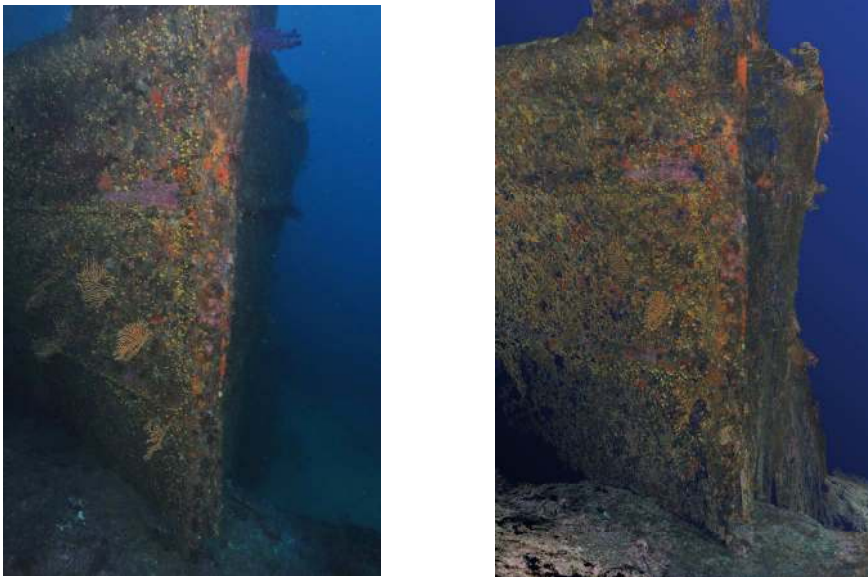

Fig. 17. On the left, one of the 1,828 digital photographs taken. On the right, the *Liban* wreck: cloud of 3D points measured by photogrammetry using the Furukawa method.
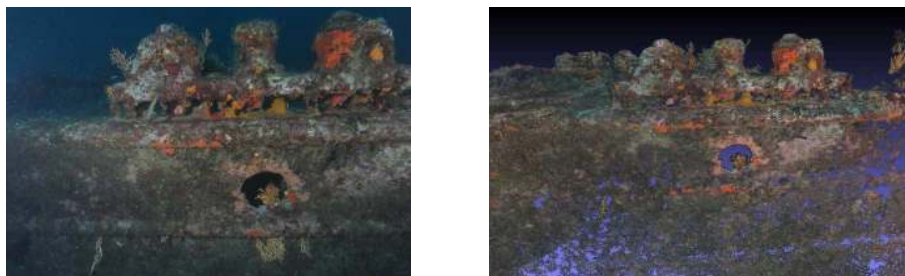
Fig. 18. On the left, one of the 1,828 digital photographs taken. On the right, the *Liban* wreck: cloud of 3D points measured by photogrammetry using the Furukawa method.

7. Conclusion

Using the computerized recordings of all excavation data, archaeologists are now able to obtain accurate 2D or 3D representations and interact using faithful facsimiles built close to the ground and viewable using standard software.

But beyond the process of underwater photogrammetry dedicated to artifacts, we must remember the concept of a template, or theoretical model, from which facsimiles of artifacts are generated from a limited number of measured points that provide their positions, orientations and geometrical parameters. Namely, all the visible amphorae and fragments are modeled from a concept, enriched by the measurements of each object, with its own attributes and characteristics. It is this principle, founded on rationality, which gives an archaeologist the possibility to view an entire site, which so far he has only seen a few fragmented views through a diving mask.

A rule-based engine manages the computation of intrinsic attributes according to a given geometrical primitive measured by an expert. Thus the resulting model supports to varying degrees the merging of measurements and theoretical knowledge. The final model can offer a complete graphic representation of an object seen only partially (in archeological sites, objects can almost never be seen completely because they are usually partially destroyed or eroded).

Of course, even if the representation of artifacts is complete, it is always possible to know whether an attribute has been measured or if its value comes from the theoretical model.

Persistent data is based on the notion of a theoretical model of the objects identified. We use a hybrid relational and semi-structured language (MySQL and XML) to evolve into the near future, to a PostgreSQL system to manage spatial locations, and an XML / CIDOC Conceptual Reference Model (CRM) for greater interoperability with the world heritage.

The graphic documents, 2D or 3D, dedicated to the survey representation are also very different in nature. Their function is double; first to help understand the site by providing a comprehensive and thematic overview, second to interface with data entered by the expert, allowing reasonable access to a set of heterogeneous data.

Moreover, the survey, still done manually with annotations from experts, incorporates certain mistakes due to human factors during the measurement process or during the identification of the object or fragment. A mechanism for detecting inconsistencies and a set

of proposals needed to restore consistency are made available to experts during the measurement phase and also in the analysis phase of the data.

Finally, the recent advances in photogrammetry and computer vision, mainly in automatic matching and dense map generation, will change the way underwater sites are surveyed. The link between measurement and knowledge will be done using both a dense cloud of 3D points and a set of oriented photographs. Under these conditions, pattern recognition will be performed both in 2D and 3D on images and will become more robust.

8. Acknowledgements

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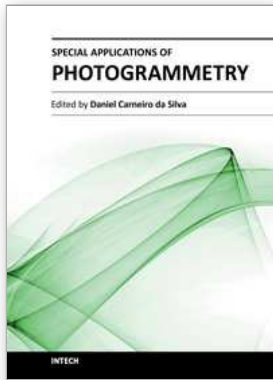
Special Applications of Photogrammetry

Edited by Dr. Daniel Carneiro Da Silva

Photogrammetry is widely accepted as one of the best surveying methods to acquire tridimensional data without direct contact with the object, but its high operational costs in equipment and personnel somewhat limit its application in mapping. However, with the development of digital photogrammetry in the 1990's, it was possible to introduce automated processes and reduce the personnel costs. In the following years, the cost of computer hardware, digital cameras and positioning sensors has been lowering, making photogrammetry more accessible to other engineering fields, such as architecture, archeology and health fields. This book shows the results of the work of researchers from different professional backgrounds, which evaluate the uses of photogrammetry, including issues of the data, processing, as well as the solutions developed for some surveying types that can be extended to many applications.

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