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# Volumetric models from 3D point clouds: The case study of sarcophagi cargo from a 2nd/3rd century AD Roman shipwreck near Sutivan on island Brač, Croatia☆

Aleš Jaklič [a], Miran Erič [b], Igor Mihajlović [c], Žiga Stopinšek [a], Franc Solina [a,] *

[a] Faculty of Computer and Information Science, University of Ljubljana, Večna pot 113, 1000 Ljubljana, Slovenia
[b] Institute for the Protection of Cultural Heritage in Slovenia, Metelkova 6, 1000 Ljubljana, Slovenia
[c] Department for Underwater Archaeology, Croatian Conservation Institute, Nike Grškovića 23, 10 000 Zagreb, Croatia

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ABSTRACT

Multi-image photogrammetry can in favorable conditions even under water generate large clouds of 3D points which can be used for visualization of sunken heritage. For analysis of under-water archeological sites and comparison of artifacts, more compact shape models must be reconstructed from 3D points, where each object or a part of it is modeled individually. Volumetric models and superquadric models in particular are good candidates for such modeling since automated methods for their reconstruction and segmentation from 3D points exist. For the study case we use an underwater wreck site of a Roman ship from 2nd/3rd century AD located near Sutivan on island Brač in Croatia. We demonstrate how superquadric models of sarcophagi and other stone blocks can be reconstructed from an unsegmented cloud of 3D points obtained by multi-image photogrammetry. We compare the dimensions of stone objects measured directly on the corresponding 3D point cloud with dimensions of the reconstructed superquadric models and discuss other advantages of these volumetric models. The average difference between point-to-point measurements of stone blocks and the dimensions of the corresponding superquadric model is on the order of few centimeters.



## 1. Introduction

Documentation of material heritage is one of the primary tasks in archeology which enables its subsequent analysis and interpretation. In accordance with the technical development, archeological documentation of sites and artifacts has proceeded from manual measurements and drawings to photogrammetry, geodetic measurements, aerial photography, satellite images and to various radar technologies that can image the earth surface even when it is hidden under vegetation or can detect structures that are hidden under the earth's surface. Corresponding active measurement techniques under water, such as sonar, have soon found their place in under-water archeology. All these remote sensing technologies are suitable primarily for discovery of possible archeological sites and for larger artifacts. Through technological progress other methods of detailed 3D documentation using active scanning techniques became available. However, most of these active methods, employing lasers or structured light, are not suitable for under-water application. There have been some isolated experiments with using structured light under-water (Roman et al., 2010; Bruno et al., 2011) but not in an actual under-water archeological campaign. Photogrammetry remains therefore the most promising technology for 3D documentation under-water, especially in the light of the most recent developments in automatic multi-image photogrammetry and since under-water photography is already an established and cost effective technology.

Under-water archeology which discovers, documents and analyses human cultural heritage which is hidden under water in rivers, lakes and seas started to develop in the 60-ties of the 20th Century, only after SCUBA diving equipment has become widely available. First under-water archeological research on the Eastern coast of the Adriatic Sea also started in the 60-ties (Erič et al., 2013). Similar as in dry-land archeology, under-water archeology started

☆ For academic performance evaluation, both Miran Erič and Aleš Jaklič should be considered as lead authors of this article.

* Corresponding author.
*E-mail addresses:* ales.jaklic@fri.uni-lj.si (A. Jaklič), miran.eric@guest.arnes.si (M. Erič), imihajlovic@h-r-z.hr (I. Mihajlović), ziga@stopinsek.eu (Ž. Stopinšek), franc.solina@fri.uni-lj.si (F. Solina).

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with collecting and recovering artifacts to concentrate later more on documentation and preservation of archeological artifacts in situ.

Photogrammetry was used under-water already by George Bass, one of the pioneers of under-water archeology, in the 60-ties of the 20th Century (Bass, 1966; Throckmorton, 1977; Balletti et al., 2015). At the time, photogrammetric methods required very precise alignment of cameras and therefore special construction had to be erected underwater and above the archeological site. The whole endeavor was very costly and time consuming and, therefore, photogrammetry was in practice not used in under-water archeology. Instead, manual measurement using tape measures and hand drawing prevailed in under-water archeology for quite a long time with all possible deficiencies (Holt, 2003).

Photogrammetry is almost as old as the invention of photography but it used to be a highly specialized and expensive technology in hand of surveyors based on evaluation of carefully taken pairs of stereo images. To be able to compute with the help of trigonometry the 3D position of selected points in the scene, their corresponding position in both images of the stereo pair had to be manually determined. Due to excessive technical complications and high cost, photogrammetry under-water was not practiced as much as above ground.

### 1.1. Under-water multi-image photogrammetry

The development of computing, in particular of computer vision, brought new image processing methods that enable automatic detection of corresponding points (tie points) in a large set of partially overlapping images. This approach to photogrammetry is called multi-image photogrammetry (McCarthy, 2014) and is based on the principle called "structure from motion". If corresponding image points can be automatically identified on a large set of partially overlapping photographs, optical properties of the camera can also be automatically established (camera calibration), as well as the relative 3D position of points for which at least two corresponding points in two overlapping images have been found. Corresponding points in images are identified with the help of the SIFT algorithm (Lowe, 2004) which works even if images have different magnification and orientation. Since 2010 many commercial and open-source software programs exist for this purpose (Kersten and Lindstaedt, 2012a; Remondino et al., 2014).

The output of these programs is a dense 3D point cloud which can be covered with texture from the original photographs. Based on such textured 3D information one can generate views of the captured scene from any viewing direction to perform virtual fly throughs, which helps in archeological analysis but also brings cultural heritage to the attention of general public (Remondino et al., 2008). In the past, cameras had to be calibrated before photogrammetric methods could be used. Most camera lens have some optic distortion, radial distortion of lens with a short focal length, which are generally used under-water, is most common. Modern photogrammetric programs have built-in parameters for correction of radial distortion of lens so that the input photographs can be corrected at the same time as the photogrammetric computation is performed. The problem with photographs taken under-water is that entirely different types of distortion can appear due to refraction, when light transverses from water to glass of the camera housing, then to air and again to the glass of the lens. Optical properties of water are dependent also on temperature and salinity of water. However, if a spherical dome is used over the photographic lens, the additional distortions due to taking images under-water are similar to radial distortion. Therefore, photogrammetric programs that were designed for above ground use and that can perform automatic camera calibration can also be successfully employed under-water (McCarthy and Benjamin, 2014). Due to changing optical conditions under-water it makes sense, therefore, to use the functionality of automatic self calibration of cameras from the set of input images.

Above ground, one can take photographs suitable for photogrammetric reconstruction also from a greater distance. Underwater, however, we are limited by the reduced visibility. Limited visibility under-water is the result of light absorption (loss of light energy) and of light scattering (change of direction of light rays). Absorption and scattering is not caused just by water molecules but mostly by tiny particles that hover in the water. Even in very clear water, one can not see much further than 20 m, and in turbid waters, the visibility can drop to one meter or even less (Schettini and Corchs, 2010). This circumstance means that we must take photographs for photogrammetric reconstruction under-water from smaller distances which means that a larger number of photographs of sufficient quality for corresponding point identification must be taken. To cover a larger portion of a scene from a smaller distance, lens with a shorter focal length are preferred therefore in under-water photography. With greater depth the visibility under/water is not reduced in a linear fashion. The colors drop off one by one, depending on the wavelength of the color. The blue color travels under-water the farthest due to its short wavelength, while the red color is absorbed in just a few meters. Images taken underwater have therefore a distinct blue-green tint. Image processing methods can improve up to a degree the quality of images taken under-water, their sharpness as well as their colors. Methods based on physical principles of image formation under-water do not give any better results than methods using subjective qualitative criteria (Schettini and Corchs, 2010). Furthermore, the latter methods are also simpler and faster. In practice, proper camera settings of white balance etc. are often sufficient for taking images for under-water photogrammetry (Balletti et al., 2015).

Automated multi-image photogrammetry is emerging as an important archeological tool in general since it offers significant reductions in the cost of archeological survey (Kersten and Lindstaedt, 2012b; Skarlatos et al., 2012; McCarthy, 2014). The methods of automated multi-image photogrammetry survey are steadily moving out of academic context, where they were developed by computer vision researchers, into the hands of heritage professionals who try to include these methods into the workflow of an entire excavation process, in order to record, document and visualize the excavated archeological heritage (De Reu et al., 2014; Remondino et al., 2012). The most recent systematic study of using multi-image photogrammetry under-water from a technical viewpoint was written by McCarthy and Benjamin (McCarthy and Benjamin, 2014). Most published studies on the use of photogrammetry under-water are based on particular under-water archeology campaigns, most of them documenting ancient shipwrecks (Green et al., 2002; Canciani et al., 2003; Drap et al., 2007; Diamanti et al., 2013; Mahiddine et al., 2013; Seinturier et al., 2013; Balletti et al., 2015). A broad picture of how multi-image photogrammetry fits into an investigation of a complex shipwreck, including a historical overview of shipwreck archeology, is given by Demesticha et al. (Demesticha et al., 2014). We have also recently successfully used such a method in lieu of manual measurements to document the wooden parts of a Roman barge in river Ljubljanica at Sinja Gorica (Erič et al., 2014a).

### 1.2. Modeling of the 3D point cloud

The result of multi-image photogrammetric reconstruction is a large 3D point cloud which can be covered by photographic textures from the images used in the reconstruction. Based on such textured 3D information one can generate views of the model from any direction and perform virtual fly throughs, which helps in archeological analysis but also brings cultural heritage to the attention of general public. Such visualizations are excellent, however, for further archeological analysis when the focus is on details, the entire 3D point cloud can be difficult to work with. One can easily measure distances between individual points in a 3D point cloud but for interpretation and understanding of the entire scene, the points should be segmented so that individual groups of points correspond to individual parts or objects in the scene. This has been a much studied problem in computer vision (Bajcsy et al., 1990) since it makes the problem of visual object recognition much easier to tackle. Points belonging to individual parts can then be modeled with more compact surface or volumetric models.

For example, from a 3D point cloud of an entire sunken ship, we would like to effortlessly separate first the points that lie on the sea bottom from the points corresponding to the wreckage. Next, we would like to separate points that belong to each individual cargo object or construction part of a ship, such as planks, floor and side timbers, chine-girders etc. and fit to these individual point clouds an appropriate shape model. Automatic segmentation of complicated shapes of such wooden construction parts of a vessel is still not possible. In the case of the Roman wooden barge which was found in river Ljubljanica and that we documented under-water (Erič et al., 2014a) such segmentation of the 3D point cloud had to be performed manually (Erič et al., 2014b).

In ancient sea shipwrecks wooden construction parts are rarely preserved. Well preserved are usually cargo items such as amphorae and stone blocks. Various semi-manufactured stone goods represent one of the most important segments of antique maritime trade. Stone products were, if possible, transported by sea or rivers. More than fifty shipwrecks holding stone products have been found so far in the Mediterranean sea, but the most widespread cargoes are still cargoes of architectural elements (Parker, 1992). Quality stone, such as marble, usually arrived from the Aegean basin and from Asia Minor. The large number and density of shipwrecks on the western side of the Peloponnese, shipwrecks in the Bay of Taranto and on the eastern side of Sicily point to Italy as the main market of quality marble.

Rectangular or cylindrical stone blocks have a regular shape that can be easily modeled with standard geometrical models. A certain amphorae type has also a uniform shape. The cargo on ancient ships consisted usually only of a very limited number of different types of amphorae, but their number could go into hundreds. Using the explicit shape models of amphorae from a particular shipwreck, the segmentation of the 3D point cloud of that site into individual amphorae models could be performed much easier (Canciani et al., 2003; Drap et al., 2007; Drap and da Silva, 2012; Diamanti et al., 2013; Demesticha et al., 2014).

The 3D points that correspond to marble blocks and columns of two marble wrecks in Sicily were also explicitly modeled with polygonal reconstructions (Balletti et al., 2015). Another example is the surface extraction of an aircraft fuselage from a 3D point cloud belonging to an under-water aircraft wreck near Marseille (Seinturier et al., 2013). In all these cases the 3D point data assigned to each part was usually segmented manually before a model was reconstructed from the 3D points. These models can then be measured in a CAD program and compared to the dimensions taken under-water during the archeological campaign. The final 3D models represent an idealized shape without concretions and seaweed. Since often the entire block can not be seen during image acquisition, such as the part in contact with the seabed, these parts are also not included in the 3D point cloud created by photogrammetry. Using a volumetric model for such a stone block, the entire shape of the block can be recreated (Balletti et al., 2015). These models also simplify the computation of the precise volume of each single item and subsequently of the entire cargo. Considering the specific gravity of corresponding stone type and its volume, one can deduce the tonnage of the ship and hypothesize its hull line. Models of the stone blocks can also be rearranged into the correct position of stowage, based on hydrostatic calculations (Balletti et al., 2015). Having explicit models of individual artifacts that consist an under-water ship wreckage has obviously many benefits for archeological analysis and intepretation.

We have developed in the past a method for simultaneous segmentation and modeling of 3D point clouds a with special type of volumetric models—superquadrics (Solina and Bajcsy, 1990). Superquadrics can model all basic geometric shapes—spheres, cylinders and rectangular blocks. We designed an algorithm that can perform segmentation and shape recovery of parametric models simultaneously (Jaklič et al., 2000). Superquadrics are used quite extensively in computer vision and robotics to model 3D shape of objects that need to be manipulated with.

We decided to test this method on a 3D point cloud obtained by photogrammetry on a shipwreck which was loaded with stone blocks and two sarcophagi. Stone blocks which have a nice regular rectangular shape seem to be ideal test objects for the method. The archeological case study used in this article is a Roman shipwreck with sarcophagi cargo from the second half of the 2nd/3rd century AD found near Sutivan, island Brač in Croatia.

The rest of the article continues as follows: Section 2 introduces the case study used in the article, a Roman wreck with sarcophagi cargo and the frequency of stone cargo in ancient shipping in general. Section 3 explains why volumetric models are helpful for further archeological analysis of such sites. Section 4 shows results of modeling sarcophagi and stone blocks with superquadrics, Section 5 discusses the advantages of using such compact volumetric models and, finally, Section 6 concludes the article.

## 2. Roman ship wrecks with stone cargo

Several shipwrecks containing a cargo of architectural elements have been found in the Adriatic. Nine stone blocks (one made of granite and eight made of limestone) were found near cape Izmetište close to Pakleni otoci, alongside pottery cargo originating from the Eastern Mediterranean. The entire cargo is attributed to the Aegean region and dated to the beginning of the 2nd century AD ((Jurišić et al., 2006), p. 181).

Eleven completed white–marble columns and few semi-finished stone blocks were found alongside a cargo of *tegulae* and *imbrices* near Susak (Vrsalović, 1974). The classical shape of these two types of roof tiles roughly date the site to the first few centuries AD ((Jurišić et al., 2006), p. 181). This wreck is currently, beside the stone sarcophagi shipwreck near Sutivan, discussed in this article, the largest stone cargo on the Eastern Adriatic coast which exceeds thirty tons.

A site comprising numerous larger stone blocks, whose regular arrangement and position on the sea bottom suggest that it is indeed a shipwreck, has recently been discovered near Splitska on the island of Brač. Other objects which could possibly contribute the precise dating of the shipwreck were not found during the survey ((Parica, 2012), pp. 350–351).

The shipwreck near Punta Scifo near Crotone in South Italy displays the variety of architectural elements as well as their provenance. Due to its small depth of five to six meters, the site was known since the beginning of the 20th Century when a part of the cargo was taken out (Orsi, 1921). Most of the extracted cargo, which varies in shape from roughly processed to almost finished and complete products, came from a quarry near the city of

Synnada in Asia Minor. The cargo consists of five censers of large dimensions, four pedestals with lion paws and eight columns of various dimensions. All elements were made of white-purple marble of the pavonazetto type, well known throughout the antique period. Only one stone block is made of white marble, but also originates from the quarries near Synnada. The marble from the island Proconessus in the Sea of Marmara is represented by two altars or pedestals and by two rectangular blocks. This marble cargo which came from different quarries was probably loaded in the same harbor and afterwards transported to the West. According to consular inscriptions found on one of the columns, the shipwreck can be dated to the 200 AD or a couple of years later (Pensabene, 1978).

Cargoes of stone artwork are far rarer, just like cargoes of semi-finished, uncompleted sarcophagi which were formed from marble or limestone. Twenty-three sarcophagi, some of which were covered with a lid, were found at the San Pietro site, situated near Taranto in South Italy ((Alessio and Zaccaria, 1997), p. 21). According to the shape of the sarcophagi and other finds, the shipwreck is dated in the first half of the 3rd century AD ((Parker, 1992), p. 381). A second, also very important, shipwreck from Torre Sgarrata was also found in the Gulf of Taranto. It contained a cargo of 18 semi-finished and uncompleted sarcophagi, 23 large blocks and a large quantity of marble tiles ((Throckmorton, 1969), pp. 282–300). Several blocks were made from alabaster originating from Asia Minor, while the sarcophagi and white marble blocks originate from Thasos. The dating of this shipwreck was provided by bronze currency of emperor Commodus (180–192 AD), minted on Lesbos. The ship which carried the cargo weighting approx. 160 tons was around 30 m long. Numerous evident repairs and radiometric dating (77–43 BC) suggest that the ship had been in use for more than 200 years ((Parker, 1992), p. 429).

So far, three shipwrecks with a cargo of sarcophagi are known in the Adriatic. They are located in front of Veli Školj near the island of Mljet, at a site close to the island of Jakljan near Dubrovnik, and the Sutivan wreck discussed in this article.

### 2.1. *Case study: Roman shipwreck with sarcophagi cargo from second half of the 2nd/3rd century AD near Sutivan, island Brač, Croatia*

At the end of 2008 the diving club "PIK Mornar" from Split reported a wreck site near Sutivan on island Brač in Croatia to the Department for Underwater Archaeology, Croatian Conservation Institute (DUA HRZ) (Mihajlović, 2012, 2013). The Department carried out a survey of the location at the beginning of 2009. The first inspection discovered a cargo of two sarcophagi with lids, stone blocks and a stone oil jar. A proper research of the site conducted by DUA HRZ started in 2010 and continued until 2012. The operation was financed by the Ministry of Culture, Republic of Croatia, with logistic support by the Sutivan municipality. The Institute for the Protecting of Cultural Heritage of Slovenia, Computer Vision Laboratory of the Faculty of Computer and Information Science, University of Ljubljana, Rok Kovačič as photographer and XLab Research Group as provider of photogrammetric reconstruction were involved in the photogrammetric documentation and 3D modeling of the wreck.

The wreck is situated on an almost flat, sandy sea bottom at a depth of 32 m, spreading across almost 40 m$^2$. Twenty-four stone objects stacked into two layers were visible. The bottom layer was almost completely buried in the sand. During a three-year campaign, the area around the complete cargo was excavated for about 50–100 cm in depth. The depth of the cultural layer varied between 40 and 60 cm under which begins a sterile layer or, in some parts, the stone bed. The finds which emerged from within the first 30 cm of the excavated layer cannot be attributed to this shipwreck since a few hundred small lead fishing weights and nets were found inside this layer which indicate more recent fishing activities.

Finally, a complete inventory of the cargo consisting of at least twenty-four different semi-manufactured stone blocks could be made (see Figs. 1, 2, 5 and 6): there were two *sarcophagi* (object no. 3 measures 200 × 92 × 72 cm) with lids (object no. 5 measures 215 × 107 cm), thirteen flat stone blocks of different sizes probably designated for production of *stelas*, one circular stone column, a smaller funerary slab or *stela* and one stone oil jar (object no. 10 has diameter of ca. 1 m). The entire stone cargo weights around 30 tons and based on the largest overall width of the sunken cargo, the length of the ship was estimated to be 20–22 m.

The classical shape of the sarcophagi suggests their antique provenance, but since there were no other finds the precise dating of the shipwreck based on the cargo was not possible. Fortunately, the shipwreck contains also some highly rare scraps of wood construction: at least six parts of the frame (made of oak wood *Quercus* sp.) and a few parts of bottom planks (made of pine wood *Pinus Nigra*), which were analyzed by the Dendrochronology laboratory of the Department for Wood Science and Technology, Biotechnical faculty, University of Ljubljana. Radiometric dating of wood was made by Beta Analytic Inc. and the results show that the wood was cut in the middle of the 2nd century AD. Beside few ceramic finds, which can be attributed to Eastern Coarse Ware (2nd–3rd century) and a oil lamp (stamp VIBIANI), a very rare discovery of two human bones belonging to the left leg (*femur* and *tibia*) was made under one of the sarcophagus in the stern part of the ship.

### 2.2. *Manual documentation*

The site of the Sutivan shipwreck and the sarcophagi cargo were manually measured in two research campaigns. The wreck site was covered with a rigid grid of squares measuring 2 × 2 m. The grid served as a basis for measurement performed with measuring tapes. To set up the grid and to perform the measurements necessary for drawing a basic plan, around 34 diving hours were needed. Even after this effort, large discrepancies can be observed between the sketch and an orthophoto of the wreck site (Fig. 1).

### 2.3. *Documentation with multi-image photogrammetry*

During the 2012 campaign we dedicated an hour long dive to take a set of approx. 900 photos of the circa 110 m$^2$ area of the wreck site with the aim to use them for multi-image photogrammetry (Mihajlović, 2013). The pictures were taken with a digital SLR camera Nikon 300 during a single dive. Due to the changing illumination it is advisable to take the photographs for a single multi-image photogrammetric reconstruction in a short period of time. Then the identification of tie points in overlapping images, which is needed for photogrammetric reconstruction, can be more reliable (Balletti et al., 2015).

The 3D point cloud (Fig. 2) was produced from the acquired image set with the commercial application PHOV (now Mementify), a product of companies Xlab Research and 3dimenzija (Erič et al., 2013). The PHOV software package performs auto-calibration of the camera in parallel with the reconstruction of the 3D point cloud.

The method of 3D reconstruction from a series of images consists of three main phases:

(a) determination of tie points in overlapping images using a derivation of the original SIFT algorithm (Lowe, 2004),
(b) dense 3D point cloud calculation in parallel with camera calibration using bundle adjustment (Triggs et al., 2000), and

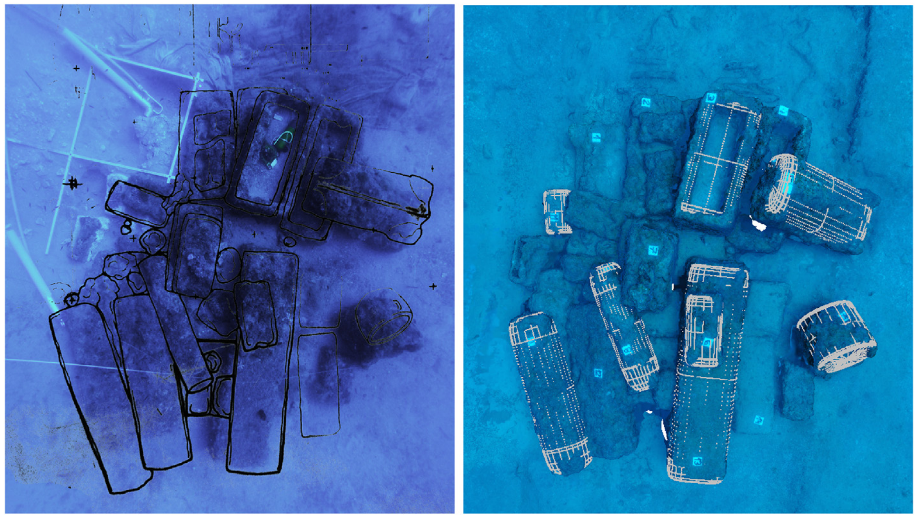

**Fig. 1.** Roman shipwreck with sarcophagi cargo from second half of the 2nd/3rd century AD near Sutivan, island Brač, Croatia. On the left is the orthophoto of the Sutivan shipwreck at an early stage of the archeological campaign since fishing nets that got entangled into the stone blocks are still visible on the top of the image. Black outlines indicate the sketch made under-water, based on manual measurements. The differences between the sketch and an orthophoto show discrepancies of up to 50 cm. Since the wreck site is at a depth of 30 m, the sketch of the entire site already required quite a lot of effort on the part of the divers. On the right is the photogrammetrically obtained 3D model covered with photographic texture and overlaid with superquadric models which are the topic of this article.

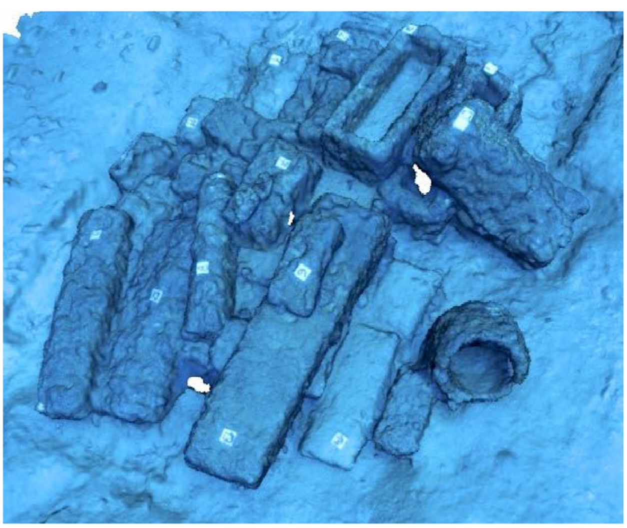

**Fig. 2.** The 3D point cloud of the Sutivan sarcophagi wreck site, shown as a 3D mesh covered with photographic texture, was produced with multi-image photogrammetry.

(c) meshing the dense point cloud using triangulation and mapping of texture from original images.

The 3D point cloud/3D mesh was then manually scaled using existing control points from the under-water site. The 3D point cloud was not geo-referenced.

When comparing the manually drawn sketch (Fig. 1 – left), which was completed in 2010, with the 3D point cloud, constructed out of 900 photographs by the PHOV Mementify software in 2012 (Fig. 1 – right and Fig. 2), discrepancies larger than 50 cm can be observed again. Manual 2D documentation required at least 30 diving hours while on the other side a series of photographs needed for the 3D reconstruction were taken during just one dive in less than an hour.

In this article we show how from this 3D point cloud volumetric models of sarcophagi and other stone blocks can be reconstructed.

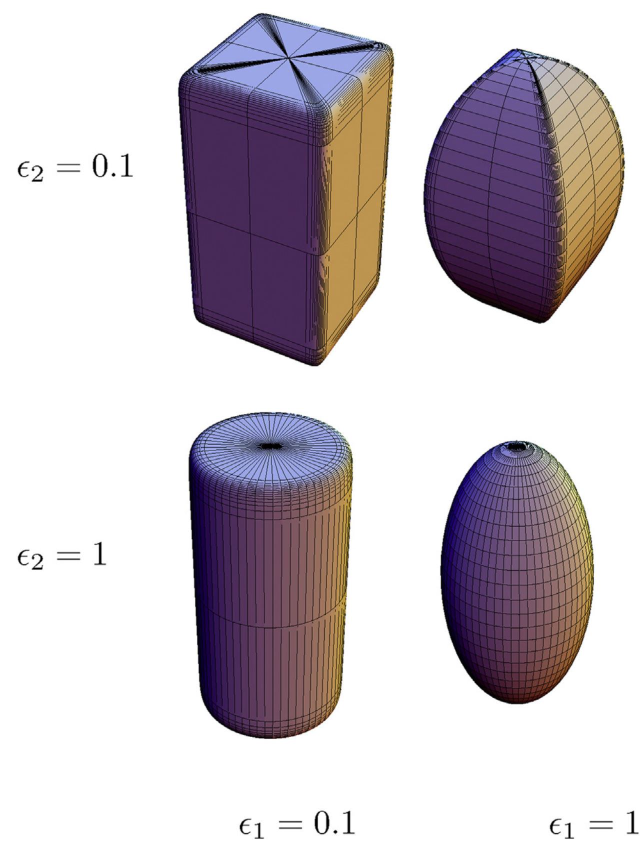


**Fig. 3.** Superellipsoids with different values of exponents $\epsilon_1$ and $\epsilon_2$. Size parameters $a_1$,$a_2$,$a_3$ are kept constant. Superquadric-centered coordinate axis $z$ points upwards!.

## 3. Modeling of individual stone blocks with superquadrics

### *3.1. Modeling of shape in computer vision*

Basic scientific methodology instigates decomposition of complex objects into parts, units or primitives to enable its study

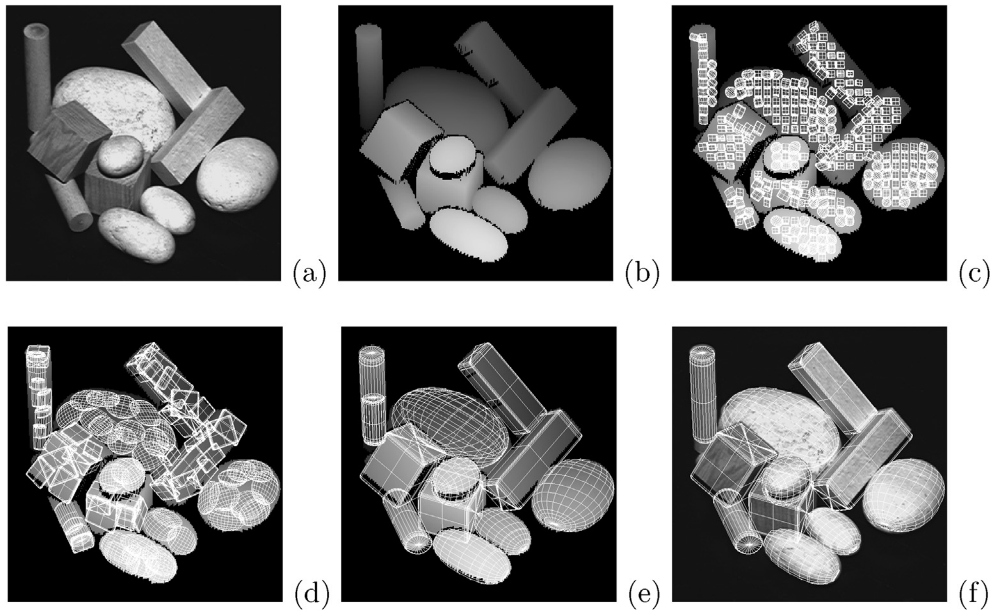


**Fig. 4.** Segmentation and reconstruction of superquadric volumetric models from 3D image of a complex scene: (a) intensity image of the scene; (b) range image—3D points of the scene; (c) initial superquadric seeds overlayed on 3D points; (d) and (e) intermediate steps in the iterative procedure; (f) final result of superquadric reconstruction and segmentation (Jaklič et al., 2000).

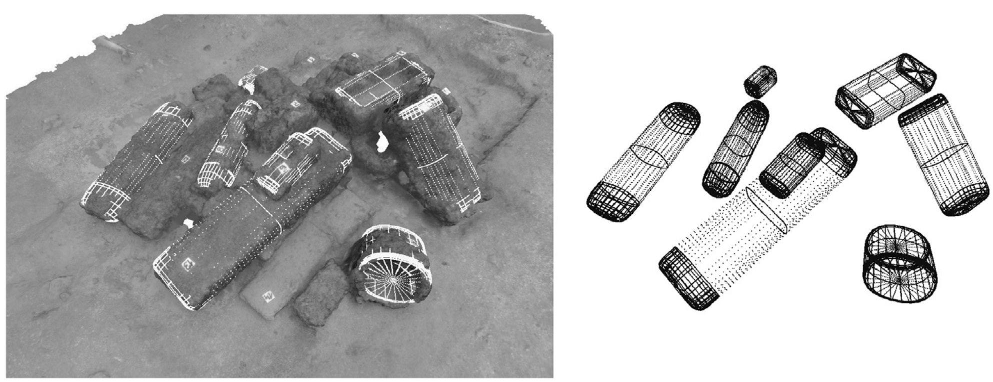

**Fig. 5.** Sutivan sarcophagi cargo modeled with volumetric models, left: superquadric models superimposed on the 3D point cloud, right: superquadric models.

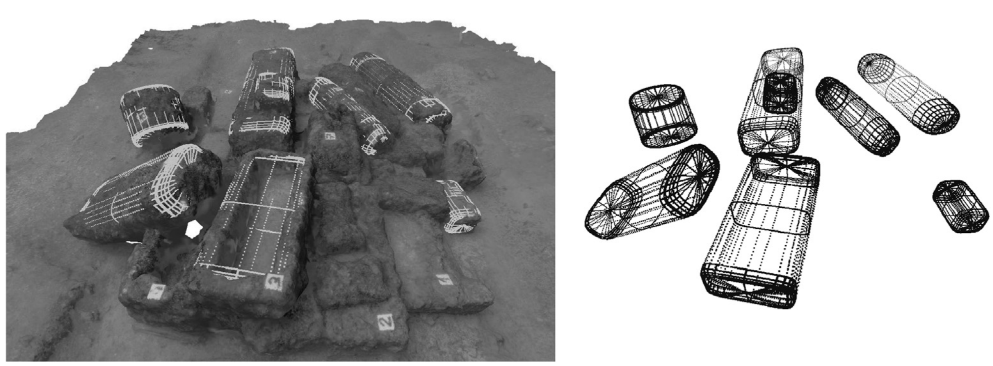

**Fig. 6.** Sutivan sarcophagi cargo modeled with volumetric models seen from the opposite view direction.

at various levels of abstraction. Abstraction is a crucial mechanism to cope with limits on how much information one can process at a time. In a similar way, to comprehend images, they should be decomposed into “natural” and “simple” parts that order and partition visual information into a limited number of perceptually significant parts. This challenging problem is called segmentation. Essential to segmentation is that the resulting parts ought to correspond to the underlying physical part structure of the scene depicted in the image. This is a prerequisite for image understanding. It is also essential for archeological analysis. In the context of our case study we would like to separate/segment the 3D point cloud of the entire wreck site into sub-clouds that correspond to individual sarcophagi so that for each 3D point sub-cloud we could reconstruct an appropriate volumetric model. Part-level description of an image is therefore a necessary step towards building the scene description in terms of symbolic entities.

So far, many different models have been used for modeling different aspects of objects and scenes. Models for representing 3D structures can be grouped into local and global models. Methods for local representation attempt to represent objects as sets of primitives such as surface patches or edges. Global methods on the other hand attempt to represent an object as an entity in its own coordinate system. When objects of such global models correspond to perceptual equivalents of parts, we speak of part-level models. Several part-level models are required to represent an articulated object. A part-level shape description supports spatial reasoning, object manipulation, and structural object recognition. People often resort to such part description when asked to describe natural or man-made objects (Pentland, 1986). For interpretation of clouds of 3D points, volumetric models are a natural choice for modeling parts. Such part descriptions are generally suitable for path planning or manipulation—but also for analysis and understanding of a scene, in this case a wreck with cargo of stone blocks where each block should be modeled individually.

To obtain part-level descriptions of a scene *two* tasks must be accomplished. The image must be partitioned into areas corresponding to individual parts (stone blocks in our case)—a problem referred to as segmentation—and reconstructing a part (volumetric) model for each of those segments. Normally, these two tasks are separated so that segmentation is performed first and then followed by modeling of isolated segments separated in the first step. But in this sequence, segmentation cannot take directly into account the shapes that the part-models can adopt. Adequate part-models for all image segments may even not exist in the selected modeling language. For example, if we perform segmentation manually, we may include in a 3D point sub-cloud also points that do not lay on the surface of the stone block that we intend to model, but also on the sea bottom or on some other blocks. Then, the reconstructed volumetric model can not fit well to the selected sub-cloud of 3D points.

To avoid this problem, segmentation and part-model reconstruction can be combined so that images are segmented only into parts which are instantiations of selected part-models. This means that points from a 3D point sub-cloud corresponding to a particular stone block could be deleted from it or added to it.

### 3.2. Superquadrics as volumetric models

Superquadrics are volumetric models that can, with a fairly simple parameterization, represent a large variety of standard geometrical solids as well as smooth shapes in between (Barr, 1981; Pentland, 1986; Solina and Bajcsy, 1990). This makes them convenient for representing rounded, blob-like shaped parts, typical for objects formed by natural processes but also for rectangular or cylindric man-made objects (Fig. 3).

Superquadric models in combination with global deformations are like a set of primitives which can be molded like lumps of clay to describe the scene structure at a scale that is similar to our naive perceptual notion of *parts* (Pentland, 1986).

The implicit equation, where $a_1$,$a_2$ and $a_3$ determine the size along each axis, while $\epsilon_1$ and $\epsilon_2$ determine the global shape, is called also the *inside-outside* function:

$$\left(\left(\frac{x}{a_1}\right)^{\frac{2}{\epsilon_2}}+\left(\frac{y}{a_2}\right)^{\frac{2}{\epsilon_2}}\right)^{\frac{\epsilon_2}{\epsilon_1}}+\left(\frac{z}{a_3}\right)^{\frac{2}{\epsilon_1}}=1. \quad (1)$$

Points *x*,*y*,*z* that correspond to the above equation are on the surface of the superquadric.

A superquadric centered in the origin of the coordinate system is defined by five parameters (three for size in each dimension, two for shape defining exponents). For a superquadric in general position, six additional parameters are required, three for translation and three for rotation of the model.

Superquadric models, which compactly represent a continuum of useful forms with rounded edges, and which can easily be rendered and shaded due to their dual normal equations, and deformed by parametric deformations, were used first in computer graphics (Barr, 1981) and later adopted in computer vision and robotics due to the ease of their reconstruction from 3D data (Pentland, 1986; Solina and Bajcsy, 1990; Jaklič et al., 2000).

### 3.3. Reconstruction of superquadrics from 3D points

The problem of reconstructing superquadrics from 3D points is an overconstrained problem. Eleven superquadric parameters must be determined from a few hundreds or thousands of 3D points, that are positioned on the surface of an object, and they should be positioned as close as possible to the surface of the model. If the shape of an object modeled by a superquadric does not conform exactly to the shape of the superquadric, then some points from the object's surface will be positioned outside of the superquadric model and some points will be positioned inside of the superquadric model (see, for example, Fig. 7). By their parameterization the superquadrics impose a certain shape symmetry and in this way place some reasonable constraints on the shape of that portion of the modeled object which is not covered with 3D points.

Stone blocks in our case study are laying on the sea bottom and therefore we can not recover any 3D points from their bottom surface. Although we can take images for the photogrammetric reconstruction from all sides around the scene so that there is no self-occlusion, there are some stone blocks that may partially occlude each other. Superquadrics can model also the “missing” parts of stone blocks using the self-imposed symmetry of superquadrics.

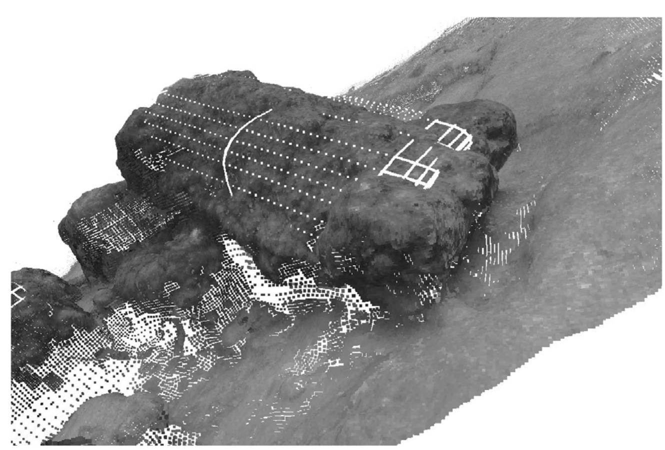

**Fig. 7.** A detailed view how the supequadric model fits the sarcophagi lid (object no. 5). The superquadric model is partially occluded by 3D points since the superquadric model takes on the average shape in a least-squares fashion, so that some 3D points are inside the superquadric model (the SQ model is obscured by 3D points) and some 3D points are outside the model (the SQ model is visible).

With an iterative, non-linear least squares fitting technique using as the fitting function, the modified implicit superquadric function (Eq. (1)) with an additional multiplicative volume factor one can achieve the reconstruction of the *smallest* superquadric model for a given set of 3D points (Solina and Bajcsy, 1990; Jaklič et al., 2000). Reconstruction of a single superquadric model requires on the average about 10 iterations.

### 3.4. Segmentation of superquadrics

Segmentation entails decomposing images into segments so that each piece of information in an image is mapped either to a segment or discarded as noise. To get as compact a description as possible a minimum number of such part primitives should be used. To define what is "natural" and "simple" is a hard problem. It depends on the type of the observed scene as well as on the objective of the observing agent. The general segmentation problem is very difficult since multiple sources of image information should be involved. In this article we restrict ourselves solely to the use of 3D points.

We developed a method for simultaneous segmentation and reconstruction of superquadric models initially from range images. Segmentation of range images is simpler because the neighborhood of range points in the x–y plane is well defined, while the neighborhood determination in a point cloud takes an additional computational step. However, reconstruction of superquadrics from several range images (Zhang, 2004) or even from a 3D point cloud is more stable and accurate because more 3D points from all sides of the object better constrains the model. We have generalized therefore our method to work also with 3D point clouds.

Our segmentation method is described in detail elsewhere (Jaklič et al., 2000). An intuitive explanation of the iterative method for superquadric reconstruction and segmentation is as follows:

1. 3D points are covered with small superquadric seeds,
2. each superquadric seed is fitted to its corresponding set of 3D points,
3. the superquadric models can in the next iteration expand, so that 3D points that are in the vicinity of the corresponding model and are compatible with the shape of the superquadric can be integrated into the model,
4. when superquadric models expand as allowed by the 3D points in their vicinity, they start to overlap,
5. a selection procedure is performed using the criterion of minimum description length to delete some superquadrics, so that in each iteration fewer superquadric models remain,
6. after a few iterations only as many superquadric models remain as are necessary by the parts structure in the 3D data.

Fig. 4 shows the initial step, two intermediate steps and the final step in the superquadric reconstruction and segmentation procedure. For illustration, the superquadrics are overlayed on the corresponding intensity image.

## 4. Results

From the 3D point cloud of the Roman sarcophagi wreck site, which was constructed with multi-image photogrammetry, shown in Fig. 2, we reconstructed superquadric models for eight objects numbered 3, 5, 6, 8, 9, 10, 11 and 13. Fig. 5 shows on the left side the reconstructed superquadrics superimposed on the 3D point cloud from approximately the same direction as in Fig. 2. On the right side are shown just the reconstructed superquadrics. Fig. 6 shows the same scene from the opposite direction.

The photogrammetrical reconstruction of the sarcophagi wreck was done when the actual archeological campaign which was using manual documentation was already concluded. Just one set of images was recorded and the photogrammetric results which were processed much later could be probably better. The 3D point cloud was probably not dense enough everywhere to reconstruct superquadrics for all objects on the scene in a completely automatic fashion. By manually initiating the growth of superquadrics also on other stone blocks the missing superquadrics could be reconstructed. We believe that better quality of data would solve the problem of missing stone block models.

Superquadrics superimposed on the 3D point cloud are not visible everywhere. This is because the modeled objects are not ideal geometric shapes and therefore some 3D points are positioned inside the supequadric model making the superquadric visible, and on the other hand, some 3D points are positioned outside of the corresponding superquadric model so that the 3D points are occluding the superquadric model. This can be observed also in the close-up view of object no. 5, a sarcophagi lid (Fig. 7).

We measured first in Meshlab the distances between manually selected 3D points in the 3D point cloud to get the best estimates of the dimensions of the selected stone blocks. The selection of appropriate points is quite tricky if the surfaces of the object are not smooth and the edges and corners are rounded. These distances should be similar to manually measured distances using a measuring tape. We compared then these point-to-point measurements with the corresponding dimension of the superquadric model.

We computed also the average error and their standard deviation as shown in Tables 1 and 2 using the following formulas, where $N$ is the number of objects:

$$error_{avg} = \sum_{i}^{N} |Point - to - point_i - SQ_i| \tag{2}$$

$$error_{std} = \sqrt{\frac{\sum_{i}^{N} |Point - to - point_i - SQ_i| - error_{avg}}{N}} \tag{3}$$

Manually, under-water recorded dimensions using a measuring tape of object no. 3 (a sarcophagus) are: 92 × 200 × 72 cm (Mihajlović, 2012). All width and breadth dimensions of the sarcophagus are in good agreement (see also Table 1). However, the manually measured height of the sarcophagus is much larger. This discrepancy can be explained by the automatic method of segmentation. The algorithm has included into the superquadric model also 3D points from the bottom of the receptacle opening of the sarcophagus so that the height of the superquadric corresponds actually more to the depth of the receptacle cavity. Such problems do not arise with regular stone blocks. For objects with a cavity, however, the cavity should be modeled as a separate entity (Solina, 1987).

Which measurement in Table 1 is more relevant depends on what is the purpose of the measurement. When measuring rough hewn stone blocks with rounded edges and corners and marine accretions, it is difficult to select representative points from which to measure, be it on the actual physical stone block or on the 3D point cloud. We tend to measure from the most exposed points. Using the dimensions of a superquadric, however, which has been fitted to the 3D points on the objects surface in the least-squares fashion, they probably give better estimates for the size of the block which is then used for the computation of the volume and subsequently for the weight of the stone block.

**Table 1**
Comparison of dimensions for rectangular stone blocks between point-to-point measures and superquadric dimensions.

| Object no. | Point-to-point measur. | | | Superquadric model | | |
|---|---|---|---|---|---|---|
| | Width [cm] | Length [cm] | Height [cm] | Width [cm] | Length [cm] | Height [cm] |
| 3 (sarcophagus) | 95.05 | 201.62 | 40.71 | 92.12 | 182.73 | 44.99 |
| 5 (lid) | 107.50 | 205.80 | 47.39 | 94.30 | 200.70 | 51.44 |
| 6 | 52.86 | 115.81 | 21.63 | 55.93 | 111.83 | 36.11 |
| 8 | 57.43 | 213.89 | 42.86 | 56.33 | 219.07 | 53.78 |
| 9 | 81.98 | 273.02 | 56.42 | 84.13 | 278.49 | 61.22 |
| 11 | 44.21 | 77.26 | 28.31 | 46.98 | 75.81 | 41.95 |
| 13 | 95.12 | 351.22 | 54.78 | 97.12 | 355.62 | 59.44 |
| Average error | | | | 3.89 | 6.36 | 8.12 |
| Standard dev. | | | | 4.16 | 5.69 | 4.71 |

**Table 2**
Comparison of dimensions for an oil jar.

| Object no. | Point-to-point measurement | | Superquadric model | |
|---|---|---|---|---|
| | Radius [cm] | Length [cm] | Radius [cm] | Length [cm] |
| 10 (oil jar) | 43.92 | 97.80 | 41.55 | 99.03 |
| Error | | | 2.38 | 1.24 |

## 5. Discussion and conclusion

It is estimated that in the Mediterranean sea only about 5–10 percent of under-water cultural heritage sites (mostly sunken ships) are registered, much less of them properly researched. In Slovenian territorial waters there are 38 registered shipwreck sites, of these, three coastal sites are partially researched and on seven sites only preliminary research was performed to date the shipwrecks. A proper under-water archeological research was not performed on any shipwreck in the Slovenian territorial sea. In the Croatian part of the Adriatic about 400 shipwrecks are registered. Only about 15 of them were properly archeologically researched.

The heritage in Slovenian territorial sea is endangered by fishing and by shipping heading towards the ports of Koper and Trieste. In both ports combined, 8000 ships have landed in 2010. Since the sea is not very deep, the danger of damaging under-water heritage sites is acute. The ships often wait to land up to several days. Almost the entire sea area in the South-Eastern part of the Gulf of Trieste is declared as a navigational corridor to both ports and as an anchorage. Damage that several ten tons heavy anchors can cause to the sea bottom habitat and heritage is evident. When the bora wind picks up to 180 km/h, anchors start to plow across the silted bottom. On batygraphic charts one can observe 3 m wide and several hundred m long tracks caused by anchors. Local divers which are familiar with the half of 38 registered shipwrecks in the Slovenian territorial waters observe every year new damage. Some estimate that in the last 20 years more than 60% of heritage was destroyed. In the next twenty years this under-water heritage may completely disappear. Accurate and timely 3D documentation using photogrammetry and subsequent archeological analysis is therefore essential to understand the archeological maritime heritage and to preserve it at least in a virtual form.

Multi-image photogrammetry will probably prevail in the near future as the most effective and cost efficient method of 3D documentation at least in underwater archeology. The huge numbers of 3D points and associated texture can offer spectacular 3D visualization (Rusu and Cousins, 2011), however, for analysis of a scene where one could understand a scene in terms of its constituent parts, necessary to grasp the construction process and the functionality of objects, their shape must be represented in a more compact fashion. Shape models that support this way ob thinking are part-level models and superquadric models are a mathematically elegant part-level models that enable automatic segmentation and model reconstruction. Therefore, superquadrics are a popular model in computer vision and robotics for some time already (Jaklič et al., 2000).

What are the benefits of using superquadric models in archeology? Superquadrics offer a level of abstraction which is advantageous for reasoning about the overall structure of a given scene—for example, how many parts there are, how are they interconnected/supported and what is the volume of these parts. Even if the wooden parts of the ship may have completely disappeared, analysis of the cargo can hypothesize the size and shape of the ship.

The advantage of supequadric models is in the automated way of segmentation and recovery which should save a lot of manual work in comparison when the 3D point cloud must be segmented by hand. Superquadrics on the other hand can not model such fine-grained shape features as a meshed model can.

Superquadric shape is defined with just five parameters which offers a very compact description making comparisons very efficient. Although superquadric parameters can not be compared directly since the parametrization of same shapes is not unique, nevertheless, superquadrics could be used for shape indexing and searching for similar shapes at the same archeological site and in databases from other archeological sites. The expressive power of superquadrics can be enhanced with global and local deformations of basic shapes allowing more detailed modeling of shapes (Jaklič et al., 2000). In the future, we are planning to add a global deformation along the $z$-axis of the superquadric model to be able to model different types of amphorae. Using the same method of segmentation and model reconstruction we would like to reconstruct from the 3D point cloud also models of individual amphorae even if they are broken and have missing parts.

For archeological analysis of a scene complete automatization of the segmentation process is not always necessary. We strive for a semi-automatic interpretation where the archeologist just indicates the general location and extension of an object in a 3D point cloud for which he would like to get a model. In the case-study presented in this article, superquadric models of sarcophagi and other stone blocks simplify the estimation of their size and computation of their volume. Measuring point-to-point distances directly on the 3D point cloud can be difficult if the edges and corners are not well defined because of their rough shape and other imperfections. By the nature of the superquadric fitting process the average dimensions of an object are reconstructed. How a superquadric model fits the shape of a sarcophago lid can be seen in Fig. 7. Using such volumetric models, one can easier make a hypothesis on the size and shape of the ship.

We believe that if archeology wants to make full use of precise and dense 3D point clouds, whose capture is now slowly becoming just a matter of technology, automatic or semi-automatic reconstruction of volumetric and other shape models of larger granularity are needed for effortless analysis and comparison of objects.

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