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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☆

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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

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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