PHOTOGRAMMETRIC SUPPORT ON AN UNDERWATER ARCHAEOLOGICAL EXCAVATION SITE: THE MAZOTOS SHIPWRECK CASE

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ABSTRACT:

This article highlights some aspects of utilizing surveying, photogrammetry and machine vision techniques for the purpose of underwater archaeological site recording. Considering typical methods, the approaches investigated here contribute in their appropriateness for rapid data production. Different approaches according to deliverables, requirements and specifications are provided at each stage. The initial methodologies applied here need to combine high versatility, dictated by the demanding underwater environment, with acceptable measurement quality, indicated by the need for metric outcomes. Main tasks of the Mazotos shipwreck project include rapid production of photomosaics for communication and overview use, artefact 3D modelling, underwater camera calibration, photo-triangulation with bundle adjustment tools as well as automatic point cloud extraction for site modelling using dense photography and video. The diversity of tasks imposes the need to follow different approaches that combine different, often open-source non-dedicated, tools. The results presented here are at the stage of initial processing outcomes, with open issues that comprise considerations for the next development stages of the project.

1. INTRODUCTION

Mapping of underwater environments has always been a fascinating task with significant work recorded in the literature (Canciani et al., 2002; Chapman et. al., 2010; Drap et al., 2007; Ludvigsen et al., 2006; Pizarro et al., 2009). Yet, archaeological site mapping using photogrammetry, still poses many difficulties, specifically when application frameworks need to be implemented in the special case of underwater excavations, where on site processing and fast data production are of high demand. In particular, the combination of 3D site mapping with the archaeological excavation documentation, which poses by default a dynamically changing environment, can be still considered to be a very challenging task for photogrammetry. To maintain metric quality of the derived products together with speed and versatility of the results during artefact removal, the proposed approaches need to vary with regards to equipment, methodologies and analysis tools. Thus the outcomes presented here are expected to be evolved together with the implemented and proposed approaches.

1.1 Mazotos shipwreck: The study area

The underwater shipwreck of Mazotos has been investigated since 2007 by a team of the University of Cyprus, under the direction of archaeologist Dr. Stella Demesticha, in collaboration with the Department of Antiquities of Cyprus and the THETIS foundation. However, the first systematic excavation was conducted the period May-June 2010, during which a detailed mapping and documentation of the findings position on a daily basis were set as main tasks of the project. These tasks set a main difference with regards to underwater archaeological site mapping, that for example allows gathering all necessary data at a first phase and subsequently post processing these at a later phase. Thus, time regarding data collection and processing was expected to comprise a significant parameter in the project tasks. The Cyprus University of Technology (CUT), Department of Civil Engineering and Geomatics undertook the underwater mapping support of Mazotos wreck. The wreck is located in southern Cyprus, situated approximately 2 miles from the coast and in 45 meters (m) depth. The ship was sunk under unknown circumstances, carrying large amphorae used to transport wine from the island of Chios (Greece) to Cyprus. The size of the exposed cargo was approximately 17 m in length and 8 m in width. Fortunately for the site engineers, the ship was laid in a sandy flat bed, nearly intact. Therefore, it can be regarded to be approximately horizontal, or more precisely, slightly inclined as the cargo is almost in position.

The archaeological requirements for the Mazotos project, as defined by the archaeologists are summarized in the following tasks:

1. Mapping of the shipwreck's condition as it was discovered and prior to the excavation.
2. Daily monitoring of the trench's process.
3. Daily artefact monitoring and mapping of the artefacts' 3D location to enable 3D reconstruction of the wreck at the stage of full ship excavation.
4. 3D measurement and modelling of the site's pertinent artefacts such as the amphorae.

To place in context the listed products required for archaeological analysis, further considerations regard primarily speed of data acquisition as well as automation of the processing chain (e.g. system calibration, measurement and modelling). Artefacts can only be removed after their location has been recorded, which means that the developed methodologies need to be fast and accurate, distinguishing these from typical mapping approaches. In addition, non-dedicated

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software outcome is desirable to facilitate 'easy' analysis and interpretation from all members of the team including the non-photogrammetrists. Data acquisition, processing and outcome become demanding particularly when considering the difficult conditions that prevail underwater. Yet there exists one cost, that for photogrammetric processing and analysis is essential, and this is the expected reduced accuracy of the results. Underwater photogrammetry has been covered in the literature covering both the topic of camera calibration (Fryer & Fraser 1986; Kotowski, 1988; Lavest, 2000; Maas 1995) as well as modelling (Drap et al., 2003). The main contributions of this paper are:

- Application of machine vision techniques in conjunction with photogrammetry for the purpose of underwater mapping.
- Implementation of open source tools as much as it is possible for under and over water modelling and analysis.
- Application of the aforementioned techniques daily and repeatedly in an underwater excavation site instead of post processing data for underwater mapping alone.

Some overall results from the proposed techniques are presented as initial samples of the expected outcomes. It should be noted that metadata of 3D datasets, which are recorded as part of the archaeological excavation log and e-preservation, which is of utmost importance, were out of the scope of this year's research framework. In particular this years research from CUT's scope, was concerned with the 3D capture methodology.

1.2 Problems and limitations

By definition photogrammetry is connected with the term 'Art' in the context that: *"Photogrammetry is the art, science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena"* (Mc Glone, 2004). The word "Art" is being used to highlight the need for sharp, net photography. Whilst this term is gradually disappearing in most recent definitions, it can be regarded that it connects photogrammetry with the concept of visibility, which is rapidly deteriorated in the depth of the Mazotos shipwreck monitoring. As an example, depending on prevailing conditions, it is not unusual for objects located at a range of 10 m to be merged with the blue background. The red part of the visible spectrum is absorbed almost completely at any distance. Divers can work for a net time of 18 minutes in that depth, before they start the decompression sequence and resurface. In addition, divers may suffer from depth narcosis which makes even simple tasks such as tape measurement readings (typical tasks in ~20 m depths) difficult to be executed. Here due to the 45 m depth, available time for data collection and human physical condition at that depth, photogrammetry is selected for the main recording tasks. Besides recording, photogrammetry's ability to perform image matching for 3D object modelling is considered to be irretraceable. Of course image-based modelling is affected by the key issues of precise camera calibration, object space control and occlusion. For example the camera needs to be calibrated within the water medium accounting for the effect of refraction (the refractive index of water can be affected by depth, temperature and water salinity). In addition, whilst it is highly difficult to establish control, it is expected that control points established underwater should be measured with an 1/3 accuracy over the whole block. Finally, in the object modelling aspect, occlusion comprises an open issue. Hidden objects can not be fully recovered; hence undercuts or lower level amphorae can not be mapped until the upper layer is removed as an example.

1.3 Underwater photogrammetry

Considering conventional photogrammetric mapping, main characteristics of underwater photogrammetry comprise the following:

- Data acquisition: Limited on-site accessibility for data collection together with the absence for operational control over the data collection (usually implemented by a non-surveyor diver).
- Illumination: Site illumination is affected by the absorption of red wavelength at a very close range (~1.5 m) even with strong artificial light sources.
- Camera calibration: Two (water and air) media data collection that affect camera calibration and accurate 3D object measurement.
- Object control: Establishment and provision of 3D control with adequate accuracy is prohibited with surveying methods such as tape measurement and 3D triletaration.
- Object measurement: Diffusion of light poses object recognition difficult at imaging ranges of up to ~10 m and sets an imaging range of 6 m for the tie point measurement.

It is indicated that in close range imaging, diffusion can be tackled with utilization of wide-angled cameras. Fortunately this ensures good geometry (wide base to distance ratio) but it can enhance the internal camera distortions as a trade off. The data acquisition experience proved that the 'correlation' between the diffusion of light (that forces us to close range photograph the wreck) with the effect of parallax (that occurs in such close range, wide-baseline situations) can not be avoided.

1.4 Previous work and existing data

The reader can find previous work regarding studies of the Mazotos shipwreck in Demesticha (2010). Here we outline a brief review. At the outset of the discovery of the wreck, the main objectives were the documentation of its state as well as the shape recording and 3D positional mapping of its amphorae. As mentioned in Demesticha (2010), drawing of the different types of the amphorae was done based on underwater measurements collected with conventional instruments such as plastic tapes, callipers, quadrant compasses and metal rulers. The final 3D product of these measurements was a revolved design.

Within this work in order to treat 3D site mapping, we selected to utilize the available Photomodeler scanner software (Canciani et al., 2002; Green et al., 2002; Drap et al., 2007) and the available DSLR Canon A620 camera. To give a sample of the data processing chain within Photomodeler, one dataset was processed with a selected number of 119 images (total number of images= 350) accumulated in three dives during two different field-seasons. The photos were collected with an orientation ranging between 45-90 degrees with respect to the sea bottom (nadir-looking) covering a total area of 17.5 x 8 m. In order to identify the amphorae, a 10 cm diameter plastic disc with a coloured cross-wire black and yellow pattern was wrapped in the rims forming a small plane utilized to manually position the amphorae in 3D space. For scale recovery, a 2 m bar and several sub bottom buoys for vertical direction were used to introduce some survey constraints to the otherwise free network. This dataset was processed with a bundle adjustment with self-calibration for 3D positioning of the 140 amphorae. To report an example of the achieved precisions, maximum standard deviations of σX= 0.034 m, σY= 0.064 m, σZ= 0.052 m have been observed among the 771 measured 3D points. Processing revealed that significant image point residuals had to be detected and removed from the process. Although bundle adjustment processing with real world datasets and the available software can be regarded as trivial; main shortcomings were related to target measurements originating from (a) the dependency of the 3D orientation of a typical 1 m in height amphora to the determination of a 10 cm diameter target plane; (e.g. any uncertainty in this small plane is propagated to the the amphora's orientation) and (b) the targets non strict rigidity and planarity (e.g. any uncertainty in point measurements affects photogrammetric triangulation accuracy). To include a control network, control was established using 1m in height plastic tubes fitted to cement blocks and subsequently measured with tape trilateration surveys and basic photogrammetry. However the low precision of the results excluded inclusion of these measurements in further implementations.

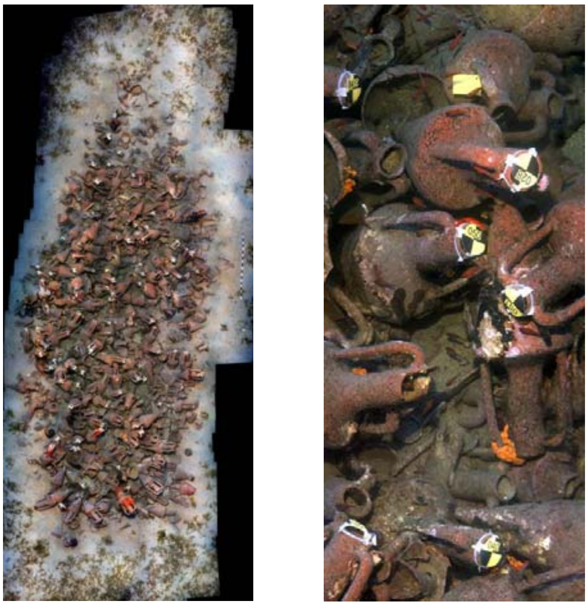

Figure 1. Photomosaic of the whole wreck (left) and plastic disks on amphorae rims detail (right) (courtesy of B. Hartzler, © University of Cyprus, ARU).

2. PHOTOMOSAICS

Extensive discussions with archaeologists and personal communication with B. Hartzler, concluded that the usefulness of the mosaics as part of the excavation process is largely related to communication and planning. The ability to explain and show the team where to go and what to do can be considered as immense in underwater excavations. In addition, it serves the purpose of site documentation particularly as the trench gets deeper and new findings are revealed. Furthermore, photomosaics comprise useful products for deformation analysis, monitoring changes that may occur amongst different excavation periods. As a result, considering the aspects of simplicity, speed and interpretation, a mosaic can be considered as a valuable product. Whilst of poor geometric quality, its radiometric quality and invisible seam lines are surprisingly good when considering the object's 1 m relief in relation to the 2.5 m object to camera distance and the utilized number of photos. However, the mosaic presents significantly low precision with discrepancies reaching ~0.9 m in comparison to control (as calculated with Photomodeler software). Several mosaics were produced within the excavation period of 2010. Photography was acquired with the available DSLR Canon A620 with fixed focus and without flash settings. Vertical photography was acquired from a 6 m distance aiming at a sidelap and overlap of 70%. It is indicated that underwater conditions often prevent even experienced divers from regular spaced photography while operating the camera equipment. As a result, the imaging range varied between 4.5 and 5.8 m within the same photo session. Image quality was considered to be poor, as a result of the diffusion effect (demand for close range photography) and coverage (demand for far-range photography). The approach followed here employs open-source or free software and it is fast enough to produce for example a mosaic composed of 50 photos, within one hour, with a minimum or no manual effort at all; setting the main product necessary to be generated on a daily basis for archeological analysis. 3D site modelling and findings positioning, although necessary, were of less significance at the present excavation process; hence these comprise primary products for our further development tasks. Figure 2 provides an example of a generated photomosaic during the period May-June 2010, repeatedly produced after every photographic dive.

Figure 2. Photomosaic of the trench (courtesy of B. Hartzler, © University of Cyprus, ARU).

It is noted that the object's relief suggests that orthophotomosaic production would require significant processing time, post processing and editing. For instance orthophoto production of a similar block would need at least 10 days on a standard softplotter. An orthophotomosaic is currently under production for comparison purposes.

3. BLOCK ADJUSTMENT

3.1 Camera calibration

Lavest et al., (2000) treat the problem of underwater camera calibration considering both air and water media. Whilst simulation can provide a good answer, the effect of refraction (the refraction index of water depends on a number of parameters such as depth, temperature and salinity) can cause unstable modelling effects in the context of the classical photogrammetric camera calibration. In our case, the camera was enclosed in a waterproof Ikelite housing with the interference of additional optics in optical line. As a result, we treated the camera-housing system as a whole. For our aim we adopted the bundle adjustment processing within the Photomodeler scanner software using the provided 0.9x0.9 m planar calibration test-field. To evaluate camera calibration, prior to the procedure we followed here, two camera calibrations were tested utilizing the camera housing and excluding the housing from the system. Data processing is expected to show whether and how housing and water interface affect determination of camera calibration. High foreground to background underwater imagery was generated with image pre-processing, particularly essential in 45 m depth where the diffusion effect is significant. The images were collected from a range of 2.5 to 3.0 m with regards to the demands for strong convergent network geometry as well as test-field frame coverage. In addition, considering that photography of the wreck would incorporate vertical (designed from an acquisition range of 5 to 6 m) and oblique imagery, an average focus distance of 3.5 m, assuming a circle of uncertainty of 2 μm, and an aperture F#1/8 were selected. Thus, objects that varied in imaging range between 2.25 to 7.82 m were marginally in sharp focus. The calibration results were utilized to initiate the block adjustment and the additional 3D measurements implemented within Photomodeler and ZI's Imagestation softwares.

3.2 Network design and planning

Personal communication with the head architect of the project, F. Vlachaki led to the consideration that one of the main tasks that the previous excavation period revealed, was the establishment of a control network. The surveying network was created by the establishment of eight 1 m tall plastic tubes fitted to cement blocks as control, measured with tape trilateration and basic photogrammetric processing. The tape measurements were processed with the Site Recorder software but its output was considered of low precision and therefore it was not utilized for any further calculations. The incorrect results were attributed to potential divers' narcosis, which may lead to fussiness (e.g. erroneous holding of the tape's zero point and recording measurements together with an inability to ensure the tape's straightness because of local currents and amphorae protrusions). However, control and check point measurement are of high importance for photogrammetric methods. The rule of thumb requires that control is of approximate accuracy of 1/2 to 1/3 over the photogrammetric block considering photo scale and the utilized camera system. In our case accuracy requirements were defined by the team of architects and archaeologists. Archeologist Dr. S. Demesticha and chief architect F. Vlachaki agreed that an accuracy of 0.05 m over the whole wreck area would suffice with photogrammetric control imposing an accuracy of 0.025 m.

Here the excavation task was focused on a 4 x 4 m trench located on the upper right area of the wreck (Figure 2) with main mapping task the daily recording of the findings position. The adopted methodology was constrained by factors such as the ability to utilize the pre-established local coordinate system, the speed of data processing (e.g. 8-10 hour processing ensuring that the position of each finding was recorded allowing for its next day removal) and the method's robustness with regards to its self-detection of erroneous points (e.g. points that have been moved unintentionally). In such a case, the best solution would be to establish a smaller network around the trench and to connect this with the previous coordinate system using bundle adjustment. Therefore, an initial bundle adjustment would use the plastic disks on amphorae rims as control for point coordinate transfer in the new location around the trench. Treating coordinates from a two-year past survey that has not been thoroughly checked together with point measurements on loosely fitted or even replaced plastic disks on the amphorae rims, is not a standard photogrammetric practice and it does carry a large risk. As this was the only feasible and economic solution available, the weighting scheme and geometry of the initial bundle adjustment were of high significance. In cases such as our, where the limited control pre-exists and is not tailor measured according to block shape, it is expected that the geometry will be poor. This fact in combination with the Photomodeler's claimed 'good' control point accuracy resulted in a remaining open issue regarding the method's quality.

3.3 Photogrammetric bundle adjustment

Nine control targets have been prepared (Figure 3) and inserted as deep as possible around the three sides of the trench leaving the fourth side clear in order to allow the divers to use the air lift for the digging process. The initial block adjustment was processed with 24 images acquired from an imaging range of 5 m and an approximate scale of 1:500. Eleven plastic disks with known coordinates were recognized from previous processing and subsequently utilized as control. The block geometry was poor due to limited control location at the two sides of the trench. Processing was implemented with the available Imagestation software with uniform control precision set at σ_{XYZ}= 0.02 m and an image measurement precision of σ_{xy}=5 μm (2 pixels). Table 1 provides sample results of one accepted solution where one control point was erroneous and rejected.

Vxy (μm)	0.001
RMS_{xy} (μm)	2.8
RMS_{XY} RMS_Z {CP} (m)	0.010 / 0.034
σ_o	4.0
σ_X / σ_Y / σ_Z (m)	0.010 / 0.011 / 0.031
Dof	513

Table 1. Bundle adjustments results

With regards to the camera model, photography and scale, bundle adjustment results suggest an acceptable RMS of 3 μm (~1.4 pixels) and a good planimetric point precision of σ_{XY}= 0.01 m and depth precision of σ_Z = 0.03 m. The a posteriori sigma naught suggests that initial precisions of input data were rather overestimated which can be attributed to the assumed control point and image measurement precisions. Main weakness of this project was the combination of the absent check points with the weak control point geometry; therefore these need to be reconsidered in the future. The 230 photo block is currently under processing in order to cross check the results obtained within Photomodeler.

Figure 3. Control point targets.

From that point forward, the daily survey of the trench covered only the trench area and its new estimated control points. It is noted that the combination of underwater diffusion and the lack of texture in the sandy bottom led to significant problems with regards to the tie point selection affecting the success of the automatic point extraction techniques. To address this problem a number of strips with coded targets were created and randomly positioned in areas with low contrast prior to the photography. For each new amphora a distinctive number of well-defined points were measured on its surface, as part of the bundle adjustment, and were subsequently passed to the architect who was manually positioning the model of the revolved amphorae, created as described in Demesticha (2010). Monitoring of the new estimated control points revealed displacements as well as slow movement, possibly attributed to the prevailing currents that were slightly but constantly pushing over protruding control points on the clay sea bottom. Again, reconsideration of control point type and measurement are open issues to be resolved in the next excavation period.

4. 3D MODELLING OF ARTEFACTS

Recording of the findings is one of the most significant tasks for the excavation process. Removed amphorae (with dimensions: height= 0.9 m and diameter= 0.35 m) are typically recorded with graphical techniques and 1:1 transfer from object to paper. With this elaborative techniques only one slice (or even half a slice in some cases) of the amphorae can be recorded. In order to improve this process and instead record the whole artefact, a number of techniques, highly advantageous over archaeological methods, have been proposed and utilised for full 3D modelling.

4.1 Laser scanning

Laser scanning utilizes a laser beam that is directed towards an object of interest by a dual-mirror system; the scanner measures the distance based on the diffuse reflection of a laser pulse from the surface to the object (Murphy et al. 2006; Ioannides et al. 2006). Different terrestrial scanners designed for scanning large volumes of objects such as buildings, archaeological sites, open mines, roads etc., characterized by their operational principle, they usually comprise expensive solutions regarding equipment and data processing. In our study we used the available Leica's ScanStation C10 laser scanner. The scanner operates based on the time of flight principle (maximum scan rate= 50,000 pts/sec, position accuracy= ±6 mm over 1-50 m working distances, surface noise= 2 mm). The scanner records a XYZ point cloud and the reflected beam intensity. Five stations were established all around the amphora in two phases by 180 degrees object rotation. Working range was set to 3-3.5 m and grid resolution to 1cm/100m. Therefore the scan data had a point density of 0.35 mm, a size of 2 million points and an estimated noise magnitude of 4 mm. The scan registration was done utilizing the four targets provided by the manufacturer and the available Cyclone software. Subsequently, the two independent point clouds were registered in a common coordinate system with an ICP-based registration (Besl & Mc Cay, 1992) and a discrepancy of 1cm. To remove noise from the point clouds a Laplace filter was applied in MeshLab software but this resulted in a detail and object geometry accuracy loss (Figure 4).

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Figure 4. 3D object mesh of amphora's.

4.2 Photogrammetry

In this test a large number of photos were processed for 3D modelling with open source software. Data acquisition time was a fraction of the laser scanner acquisition time (~1/6 to 1/8), which was important as the amphora had to stay completely wet during the process. The utilized camera was an uncalibrated 10.2 MPixel SONY A230 (array sensor: APS-C, size= 25.1 x 16.7 mm) equipped with a 18-55 mm lens. Photos were acquired with a focal length of 18mm and fixed focus during acquisition. Each phase included 36 freely acquired convergent images (two rings of 18 photos each) at a resolution of 3,872 x 2,592 pixels, sub-sampled at 2,000 x 1,128 pixels and processed automatically using Bundler (Snavely et al., 2006) and CMVS (Furukawa et al., 2010) softwares. Figure 5 illustrates a sample of the generated point cloud, noting that scale recovery was treated externally to the applied methods (e.g. scale was recovered with an adhesive measurement tape). This product was edited for background removal and ICP registration in Meshlab software, resulting in 195,000 'noiseless' intensity points. It is noted that CMVS open source software is based on a multi-image matching implementation and it only calculates points that are visible in at least three photos, therefore the implementation filters out any points that do not conform with its requirements; remaining points are considered as precise due to their high redundancy and their estimation from least square multi image matching.

Figure 5. Complete photogrammetric point cloud.

4.3 Comparison of techniques

Photogrammetry is by far the simplest and quickest method allowing for moving object removal in less than three non-stable images and posing no limitations regarding object position. The generated model presents law noise and it is easy to collect and process, hence the resultant object point density is not considered of high significance. It is, however, indicated that precise evaluation of photogrammetry and laser scanning would require ground truth (a model of higher order precision) and subsequent discrepancy estimation.

5. TRENCH MODELLING WITH COMPUTER VISION

In parallel to photogrammetry for amphora position estimation towards an 'as found' 3D model alternative methods have been tested. The vertical imagery used for bundle adjustment processing has been additionally processed with the aforementioned open source softwares (Figure 6). It is expected that additional photos with slight inclination would capture undercuts and thus provide an almost complete digital scene. The main, however, drawback of this implementation is that both scale and local reference system are arbitrary; this is expected to be resolved with control insertion. It is indicated though that this technique seems promising not only because it can automate the process and produce dense results, but because it additionally models the sea bottom on a daily basis, which is a requisite in the archaeological excavation context.

Figure 6. Automatically produced dense point cloud.

6. CONCLUSIONS AND FUTURE WORK

Photogrammetric processing has been treated both under and above water. The various implementations discussed in Mazotos project can serve underwater archaeology in different aspects that can be irreplaceable in similar applications. Moreoever, the products can support archives for future measurement tasks that are not known in advance. The proposed approaches at this stage are not mature enough though to be undertaken by inexperienced users. The present approaches are fast enough and precise in the application context. Considering time, it is indicated that within a single afternoon, two people can suffice in order to process datasets of approximately 50 photos using bundle adjustment procedures for positional recording of the findings, photomosaic production and dense 3D point cloud generation of the trench. Underwater conditions affect significantly the quality of the photos and therefore photography should be carefully addressed to avoid missing data collection areas or even dive repetition. An additional problem that needs to be addressed is control point positioning and mensuration in the sandy bottom to ensure stability. Measurement and daily control point checks are open issues as trilateration is highly unreliable in such conditions (range and almost planar network geometry). To further improve our derived products the following future extensions and improvements are under consideration:

- Point cloud generation will need to incorporate semi or fully automated procedures for automatic 3D amphora positioning.
- Speed of product delivery is expected to be treated again by automating the test approaches that simultaneously minimize manual human error.
- Automatic registration for point cloud generation in a global coordinate system is required noting that control and scale recovery are essential for a metric outcome.

Expertise knowledge needs to guide the presented frameworks to avoid erroneous collection and data processing. Our present and future investigations are expected to incorporate processing of existing video sequences towards automated video-based capture and processing using for example optical flow.

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