The Impact of the Latest 3D Technologies on the Documentation of Underwater Heritage Sites

Miran Erič*, Rok Kovačič‡, Gregor Berginc§, Mitja Pugelj**†, Žiga Stopinšek**
and Franc Solina**
*Institute for the Protection of Cultural Heritage in Slovenia
Metelkova 6, SI-1000 Ljubljana, Slovenia / miran.eric@guest.arnes.si
‡Golden Light Photography, Kult Ltd.
Cesta na Laze 14, SI-1000 Ljubljana, Slovenia / rokkov@gmail.com
§Xlab Research and 3dimenzija Ltd.
Podbreznik 15, SI-8000 Novo Mesto, Slovenia / gregor.berginc@3dimenzija.si,
†Comland Ltd.
Litostrojska 58c, SI-1000 Ljubljana, Slovenia / mitja.pugelj@gmail.com
**Computer Vision Laboratory, Faculty of Computer and Information Science, University of Ljubljana,
Tržaška 25, SI-1000 Ljubljana, Slovenia / ziga@stopinsek.eu and franc.solina@fri.uni-lj.si

***Abstract*—Documenting underwater cultural heritage is a challenging undertaking. Underwater environment is not a man's natural habitat and special equipment and devices had to be invented so that he could enter and study this environment. Several decades of underwater research and many sacrifices were needed to fully understand the importance of underwater heritage and its protection. The means for accurate documentation underwater are very limited and demanding, due to required technical equipment it is also expensive. Emergence of modern 3D methods and accompanying software tools for processing of 3D data is therefore of utmost importance for documenting and protection of underwater cultural heritage. In comparison to manual and analog methods, 3D methods offer much better accuracy, they substantially shorten the necessary time spent underwater and in this way improve the safety at work as well as lower the entire cost of field work. For illustration of the above development we discuss archeological case studies from the North East Adriatic.**

I. Introduction

The principles of cultural heritage protection have changed in the past few decades. Nowadays, technical, memorial and war artifacts are protected along cultural and archeological heritage. Awareness of underwater cultural heritage started to develop soon after the invention of autonomous diving equipment in the 1930's. Famous early films by Jacques Cousteau about the underwater world which included also shipwrecks (Épaves, 1943) [1] raised the imagination of numerous divers and archeologists all over the world. Underwater archeology and the study of cultural heritage found under water was consolidated by the discovery in 1954 of a late Bronze Age shipwreck (12th century BC) near Cape Gelidonya in Turkey and promoted by Georg Bass, Peter Throckmorton and Frédéric Dumas [1]–[3].

Just a decade later, in 1963, the first scientific survey of an underwater cultural heritage site took place on the Eastern side of the Adriatic when the Center for underwater research from Ljubljana organized an exploration of a shipwreck near Savudrija [4]. Dasen Vrsalović [5], Zdenko Brusić and Elica Boltin-Tome [6] started at that time a systematic underwater survey of shipwrecks and foreshore structures in the Eastern part of the Adriatic. One should mention also that on the initiative of Karel Dežman the first underwater archeological survey in Slovenia took place in the river Ljubljanica already in 1884 by two professional navy divers from the Austro-Hungarian naval base in Pula [7].

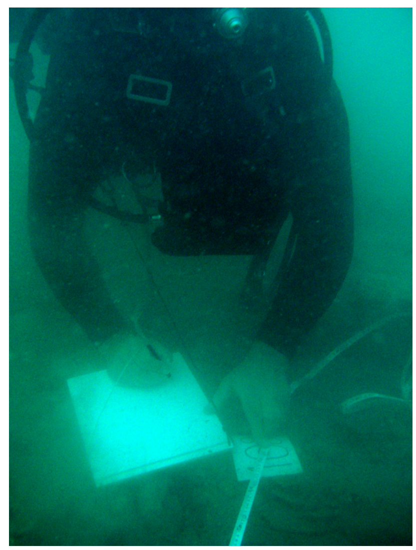

Fig. 1. Underwater heritage: Manual recording of a 19th century Barque in NE Adriatic, Gulf of Koper. (Photo: Andrej Gaspari)

Survey and documenting of underwater heritage sites in deeper and coastal waters was performed entirely manually using tape measures, spirit levels, plumb lines, measurement frameworks, drawing tablets and pens until the new millennium and often even today. Due to the desire to improve the survey of underwater cultural heritage, new measurement devices are being introduced that make the spatial localization of heritage artifacts more accurate. For the survey of larger areas remote sensing methods using sonar, radar and magneto metric devices are used. However, these devices and methods are not accurate enough for the survey of individual sites where laser and radio

978-1-4799-3169-9/13/$31.00 ©2013 IEEE

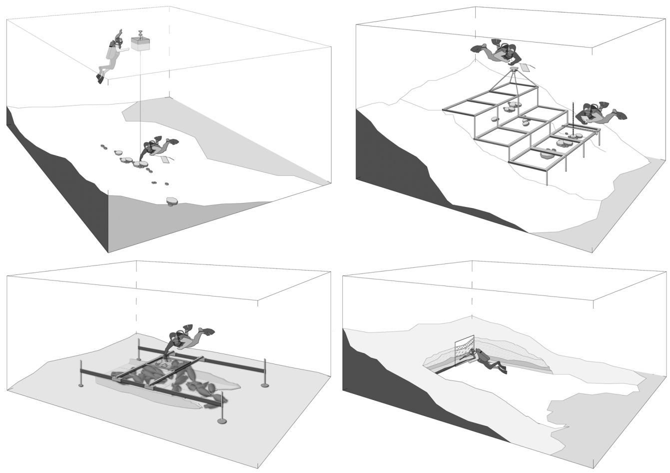

Fig. 2. Underwater heritage: Four different selected types of manual survey. (Drawing: Miran Erič [8])

based systems are employed. The small and intimate space of wreck sites has remained due to the limitations of modern sensing equipment up till recently the domain for manual survey (Figs. 1, 2).

Recent technological advances in capture of 3D data, the low cost of such equipment and, in particular, the development of open source software solutions for analysis and modeling of 3D data makes a tremendous difference to the ever underfunded underwater archeological heritage research projects. The employment of these new 3D methods enables a much faster and inexpensive survey of underwater heritage sites resulting in their much more complete and accurate documentation. This article illustrates this development using case studies from the North East Adriatic. For a survey of similar development in Greek waters see Diamanti et al. [9].

II. What Happened in the Nord Eastern Part of the Adriatic in the Last 12 Years

A. A Roman Shipwreck, Grebeni, Silba

The first full scale employment of modern survey methods in underwater archeology on the Eastern side of the Adriatic happened in September 2001 on the site of a Roman shipwreck of 1st century AD [10] next to the islet Grebeni near island Silba (Fig. 3). The Archeological Museum of Zadar initiated a collaboration with underwater archeologists from the Department of Archeology at the University of Ljubljana. For the first time, stereo photography and photogrammetry was used for surveying underwater heritage in the Eastern Adriatic. The key player in this endeavor was DFG Consulting from Ljubljana, which made available their photogrammetric software tools. At that time software tools in photogrammetry were still very expensive and since preservation of underwater heritage is not a profitable activity, these tools were normally not available to archeologists.

This collaboration demonstrated that surveying and documenting underwater heritage sites using 3D technology results in excellent and accurate models that could serve as a primary documentation of the site which could be analyzed even decades later almost as well as *in situ* (Fig. 4). The only

Fig. 3. Islet Grebeni near island Silba, 2001: Floor timbers of a Roman shipwreck. (Photo: Marko Jamnik – Mak)

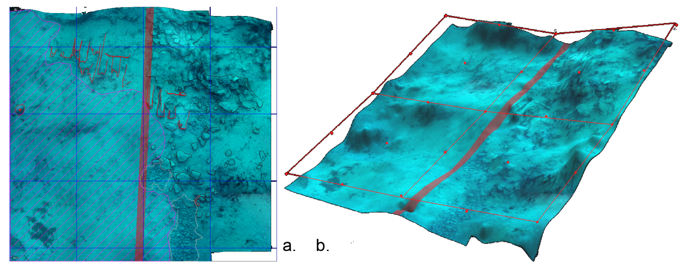

Fig. 4. Islet Grebeni near island Silba, 2001: 3D model of a Roman shipwreck site 5m×5m: (a) top-down view of the surveyed site, (b) view from the East. (3D model: Miran Erič, DFG Consulting)

disadvantage of photogrammetric software tools at that time was that corresponding points had to be entered manually. The processing was therefore time consuming and not operational enough to use it during the actual field work on an underwater heritage site.

B. Bathymetric measurements and Maona's Cemetery, Portorož

The Slovenian territorial sea is very small, it consists of merely 300km^2 and is only 34m deep and thus entirely accessible to amateur divers. It is therefore difficult to imagine that in such a small area there could be a considerable amount of underwater cultural heritage. Nevertheless, amateur divers have in the past decades identified about twenty shipwreck sites. Among these are also hydroplanes but the most famous is the ocean liner SS Rex built in Genoa in 1931 who held the westbound Blue Riband between 1933 and 1935 for the fastest crossing of the Atlantic. On 8 September 1944, off Koper, Rex was hit by 123 rockets launched by RAF aircraft and caught fire. She burned for four days, then rolled onto the port side, and sank in shallow water.

During the years 2005–2008 the company Harpha Sea Ltd. performed bathymetric measurements of the entire Slovenian territorial sea using multi beam sonar [11]. This remote sensing technology uncovered twice as many shipwrecks as they were known before (Fig. 5). Already a partial analysis of the data [12] revealed that the oldest shipwreck in this part of the Adriatic was a 15m long vessel from the 1st century AD, there is a 30m long vessel from the 14th century AD, and four vessels dated between the 16th and 19th century AD. Some shipwrecks are also from the World War I and II. The rest of

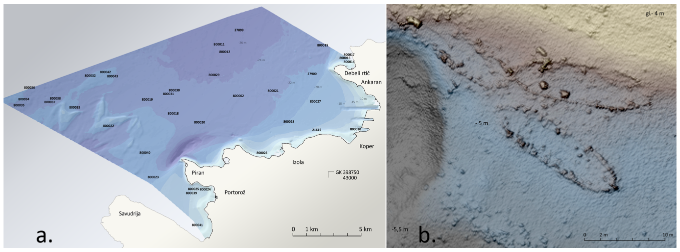

Fig. 5. Slovenian territorial sea 2005-2008: (a) Bathymetric measurement by Harpha Sea Ltd. with heritage sites, (b) Maona's Cemetery near salt warehouse in Portorož. (Bathymetric measurements: Sašo Poglajen)

the identified underwater cultural heritage sites are probably also shipwrecks which are currently still not identified. One can conclude that data obtained by sonar can substantially improve the documentation of underwater cultural heritage.

C. Roman Barge, Ljubljanica River, Sinja Gorica

The trend towards developing open source software solutions resulted also in tools for processing, analysis and display of 3D layers of data. These tools are of enormous help in modernizing the methodology of underwater archeological surveying, in getting better and more accurate results, and finally, for a more correct protection of underwater cultural heritage.

We tested this assertion in practice in October 2012 in river Ljubljanica near Sinja Gorica when we researched the extremely unusual discovery of a Roman cargo ship with a flat bottom built out of beech wood in the tradition of antique Meditteranean shipbuilding technology from year 3 AD [13], [14]. For the first time in Slovenia, we have put into practice on this underwater archeological site photogrammetric data collection, photogrammetric reconstruction and 3D modeling PHOV which was developed by the companies Xlab Research and 3dimenzija, both from Slovenia (Figs. 6, 7).

The Roman ship without cargo or other objects was cleaned of recent sediments only in the length of approximately 4.5m since the steep river bank prevented further excavation. Since the vessel is entering the bank under angle, the left side of the vessel looking towards the bank could be followed for another 3m. Based on the newly obtained data and the position of the vessel in the sediments of the right bank of the river Ljubljanica one can speculate that a further 10–12m of the vessel still lies buried.

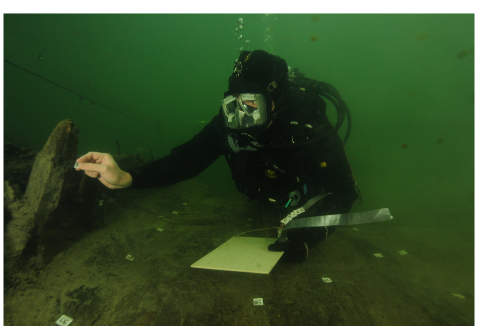

Fig. 6. Roman barge from Ljubljanica river near Sinja Gorica: Preparing the site for photogrammetric recording. (Photo: Rok Kovačič)

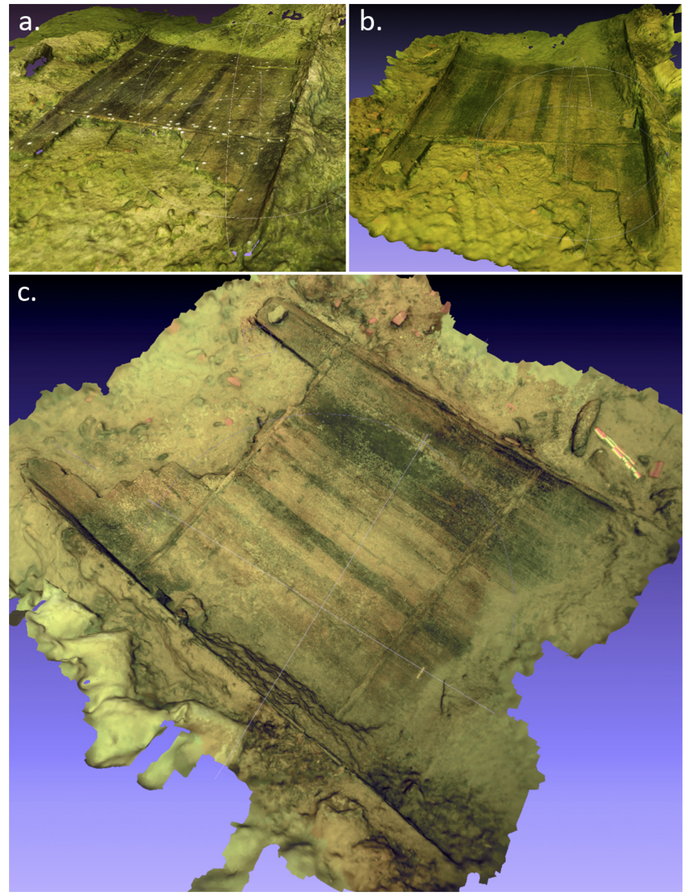

Fig. 7. 3D model of Roman barge, (a) and (b) 3D reconstructions from two different sets of photographs taken in two different days, (c) plan of the barge in perspective view. (Photo: Rok Kovačič, 3D model: Gregor Berginc, processing by PHOV, 3D view by Meshlab)

After the shape of the visible part of the Roman ship was reconstructed using photogrammetrical methods one can observe that the 3D model is exceptionally accurate and much more informative in comparison to the analog documentation which consists merely of 2D floor and side views, cross sections and detailed drawings where needed, for example of individual construction elements. The 3D model enables almost as detailed examination and analysis of the vessel as observation *in situ* (Fig. 7). Even archive photographs of extremely good quality, which are still needed, can not match the 3D model.

D. "Drevak", a typical lake boat used in the Notranjska region of Slovenia

The region of Notranjska in central Slovenia is due to its exceptional geological Karst structure blessed with interesting natural landscape phenomena such as intermittent lakes which are flooded in predictable yearly cycles. The inhabitants therefore used water for transport and a special type of a flat-bottomed boat, called "drevak", developed. The hull of this boat consists of chine–girders, which make up the entire flanks of the boat and intermediary bottom planks of width 60–100cm which extend the width of the boat to about 1.6m. This boat evolved from the dugout boat which was limited in width to about 1m due to the size of available tree trunks.

These types of boats are very important for the study of traditional water navigation in the Notranjska region as well as for the possible connections with the several thousand year old tradition of dugout boat building as well as with some construction elements of boat building originating from the Roman times. Therefore, an example of such a boat from Tehniški muzej Slovenije, Bistra, was a suitable object for comparison of different methods of 3D data capture. We built 3D models (1) using a high-resolution hand held structured light scanner Artec MHT and (2) several sets of photos for a photogrammetric reconstruction using different software tools. Experience and comparisons gained in this process will help us also in underwater research. Figs. 8 and 9 show a 3D photogrammetric reconstruction of the boat.

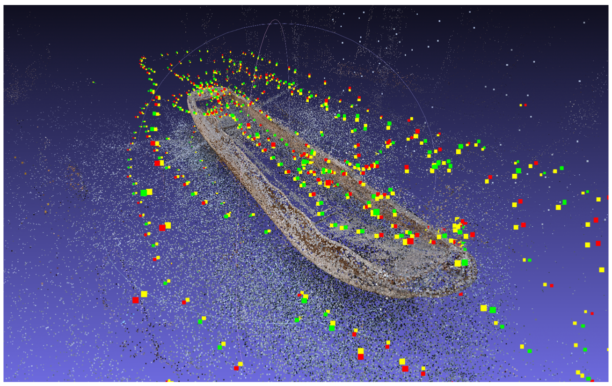

Fig. 8. Photogrammetric reconstruction of boat "drevak" in the Technical museum of Slovenia in Bistra near Vrhnika. Color points indicate the 3D positions from which the photographs were taken. (Photo: Rok Kovačič, 3D model: Gregor Berginc, processing by PHOV, 3D view by Meshlab)

Fig. 9. 3D model of boat "drevak" in the Technical museum of Slovenia in Bistra near Vrhnika (Photo: Rok Kovačič, 3D model: Gregor Berginc, processing by PHOV, 3D view by Meshlab)

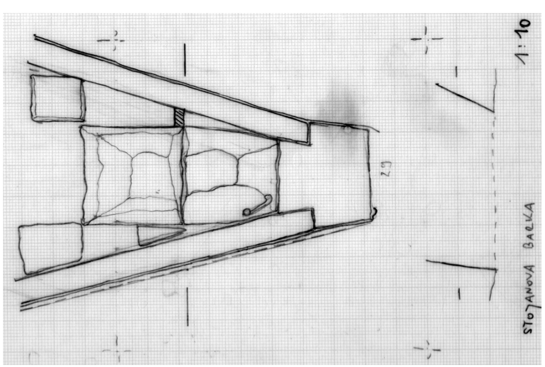

Fig. 10. Analog documentation: 2D plan drawing of a detail of a 43 m long shipwreck of a 19th century Barque (Drawing: Andrej Gaspari)

III. Underwater Heritage Sites Recording

Progress in computer technology as well as development of powerful new 3D recovery and modeling methods, in particular open source solutions, have transformed in practice the methodology of documenting cultural heritage *in situ* in the last ten years.

A. Analog Documentation in Underwater Heritage Protection

Manual data documentation (Fig. 10) was in the past, in spite of commitment to high ethical and professional standards, burdened with problems. Lengthy measurements underwater, in particular in greater depth where the operative time of individual divers is very limited, represented a serious limitation. In depths over 30m the operative time of individual divers is less than 30 minutes. In such a time frame it is almost impossible to perform correctly all procedures. Drawings and measurements are difficult to verify and therefore the scientific impact of such documentation is limited. A study of quality in underwater archeological surveys using tape measures has shown that in the case of 3D trilateration the position accuracy was 43mm [15]. However, of all tape measurements, 20% of them were found to be in error! This high error rate is without doubt due to specific underwater working conditions which lead to mis-reading or transcription errors of divers.

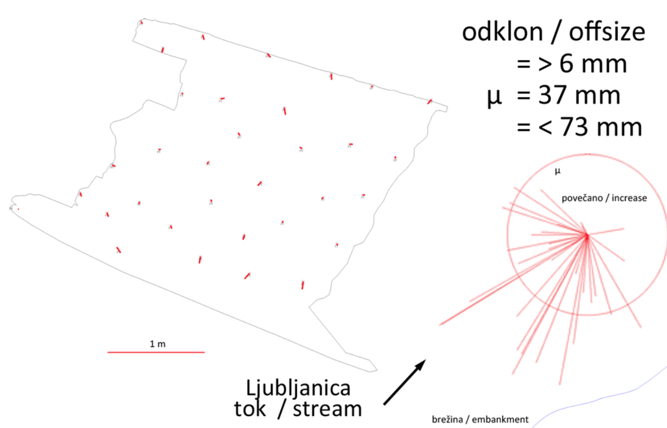

Fig. 11. Analog documentation: Differences detected during comparative analysis between the 3D model and corresponding geodetic measurements.

Despite a considerable effort spent in measurement and use of precise geodetic measurement devices (tachymeter) the comparison of these measurements to the 3D model of the Roman barge from Sinja Gorica (see II-C) [13] shows discrepancies (Fig. 11). Although the riverbed where the Roman ship lies is only 3m deep, geodetic measurements with a tachymeter were influenced by the flow of the water. This was a bitter experience since we trusted geodetic measurements up till now completely. Since geodetic measurements can not be verified the corresponding analog documentation (drawings) based on these measurements can also not be trusted completely. The use of Site Recorder [16] would probably be more accurate but it would take much longer.

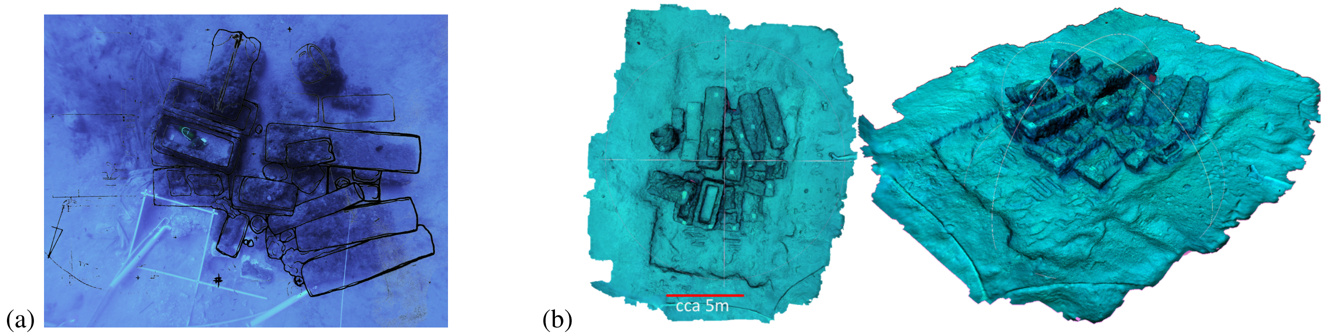

Fig. 12. Roman shipwreck with sarcophagi cargo, Sutivan, Brač: (a) differences detected between the sketch based on manual measurements and a photograph, (b) 3D model of the shipwreck from two different viewpoints. (photo: Rok Kovačič, 3D model: Gregor Berginc, processing by PHOV, 3D view by Meshlab)

Another example of how error prone can be manual methods of underwater measurement offers the comparison of manual and photogrammetric documentation of an antique shipwreck from the second half of the 2nd century AD with a load of sarcophagi near Sutivan on island Brač [17]. This ship wreckage is at a depth of 32m, the area of the shipwreck is about 15m×7m and the cargo of sarcophagi reaches up to 2m above the sea bottom. Comparing the 2D sketch plan which was completed manually in 2010 with the 3D model constructed out of 800 photographs and the PHOV Mementify software in 2012 shows discrepancies larger than 0.5m (Fig. 12). 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 in just 35 minutes.

B. The Impact of Modern Technology on Changes in the Recording Methodology of Underwater Heritage

Significant improvements in documenting underwater cultural heritage were introduced during the last decade [9], [18], [19]. These improvements enable much more detailed analysis and understanding of the heritage and at the same time also more appropriate protection and care of it. Before the emergence of more precise underwater detection and measurement technology most underwater heritage sites ware found by chance. Such sites were then documented with the help of manual measurement devices.

1) Remote Sensing of Water bottoms: Remote sensing equipment such as sonar, radar and magnetometers played a similar role in detection, recognition and recording of underwater cultural heritage in areas that could not be reached by divers as laser and optical equipment did on the surface to record the morphology of the water bottom or the surface of the earth. The Slovenian territorial waters (see Sec. II-B, Fig. 5: a.) may be small but can serve almost as a laboratory like environment for testing survey methods and equipment. The importance of recording all wrecks, especially in areas of heavy shipping traffic, can not be stressed enough. Underwater heritage sites in deeper waters are mostly shipwrecks and other sunken objects (mostly airplanes, very rarely anything else). Due to geological changes such as erosion or tectonic movements one can find in coastal waters also sunken architecture and other infrastructure.

2) New Tools for Underwater Site Recording: Until recently, the most common means for recording of data were photography, video and manual measurements to make 2D plans and maps of heritage sites. Since 1980's very accurate GIS software tools such as SiteRecorder [16] were used to measure distances and triangulate the sites in order to produce 3D CAD/GIS documentation. Unfortunately, the manual entry of measured points resulted in only a relatively small number of 3D points which enabled a "postproduction" reconstruction of an object but without any details that could be studied in the future. Development of new methods and equipment for 3D data capture such as structured light and laser scanners and outstanding results of open source photogrammetric software (PHOV Mementify, 123D Catch, Hypr3D etc.) is radically changing the approach to documenting underwater cultural heritage.

C. Latest Developments in Documenting Underwater Cultural Heritage

New technologies for capturing 3D data and open source solutions for processing and modeling such data is at the moment the most important development in documenting underwater cultural heritage.

1) Structured light scanners: Hand-held structured light scanners are currently not suitable for underwater hand-held documentation because of their technical limitations (need of an energy source, connection to a computer etc.). However, their ease of use and high accuracy helped them establish an important role in heritage documentation of land sites [20].

The main advantages of structured light 3D scanners are high data acquisition rates, high accuracy and performance independent from ambient light. The disadvantages are computational complexity, missing data due to occlusions and shadows. Monochromatic light can also bring some advantages for underwater scanning [21]. Structured light 3D scanners were also used for underwater shape measurements. Bruno et al. [22] combined a structured light laser with stereo vision Field-Of-View (FOV) optical sensor and obtained 3D models with acceptable quality despite the heavy presence of scattering and absorption effects. The experiments were made in a controlled laboratory environment but the authors suggest that the system could easily be installed on a Remotely-Operated-underwater-Vehicle (ROV), Autonomous-Underwater-Vehicle (AUV) or a submarine.

Structured light techniques can also be used to create high resolution bathymetric maps of underwater archaeological sites. Roman et al. [23] presented one of the highest resolution

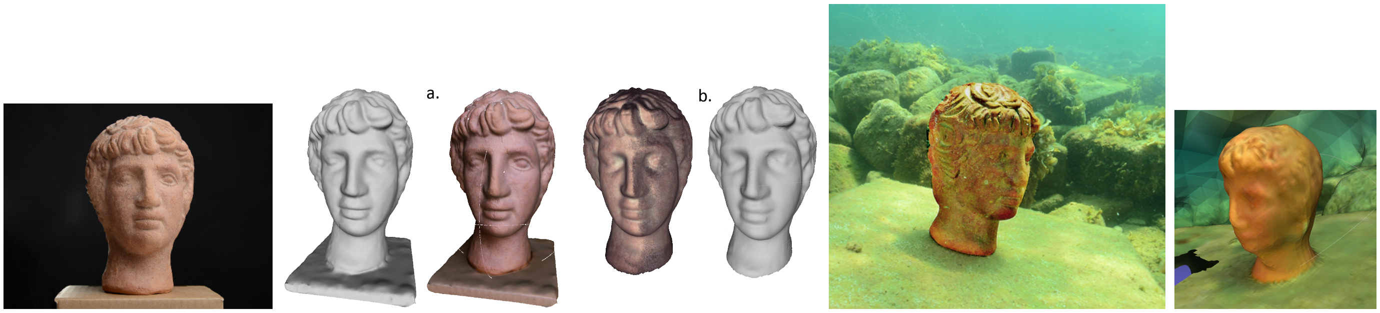

Fig. 13. Test object (left) of height approx. 30cm and different 3D reconstructions: (a) photogrammetric 3D model (without and with texture), (b) 3D model from a structured light scanner (with and without texture), underwater photograph of the test object, photogrammetric 3D model from underwater photographs (right).

bathymetric maps that have been made of submerged archaeological sites.

2) Photogrammetry: Photogrammetry used to be a very time consuming process for documenting underwater heritage. Traditionally, photogrammetry consisted of two phases, photographic data acquisition and manual registration of photographs done on a computer, requiring tremendous effort by an experienced archaeologist. Results were often available long after the excavation of the site was already finished. For an overview how underwater photogrammetrical methods evolved see Green et al. [18] and Drap [19].

To establish correspondence among images the very process of taking images had to be tightly controlled. The divers had to place a grid over the site and align the rails to slide the photographic equipment over each column, slowly covering the whole area, making sure each shot is taken at constant distance and perfect alignment with the site (Fig. 2).

Since the age of digital photography the workflow and usability of this documentation method has changed enormously. The cameras are getting smaller and the quality of images is getting better. Advances in automatic photogrammetry opened completely new horizons which relieve the user already in the first phase of the need to control tightly the process of image acquisition and from the tedious second phase by performing automatic calibration of the camera system using a series of steps, the first being the detection of distinctive image features, such as SIFT key-points [24], and finding reliable matches between photos. This information is then used to perform a series of bundle adjustment steps producing the final representation in the form of a sparse 3D point cloud and full calibration of the system in an internal coordinate system [25]. Finally, a dense 3D point cloud can be generated using the approach of Furukawa and Ponce [26].

The speed and low cost of up to date underwater photogrammetry enables continuos 3D documenting of an underwater archeology site so that 3D models can be used for daily analysis of the site to make the best cost-efficient predictions for further excavation tasks.

All the needed equipment is commonly available, reasonably priced and highly portable so that it can be managed by a single person. 3D photo modeling is appropriate for most underwater terrains but reaches its limits when visibility is less than 1m. For best results it needs constant ambient light or statically mounted artificial strobe lightning. Although on underwater sites most of the red color specter is lost in the first five meters, this can be fixed with proper lighting and color correction, so full color results can be achieved. The complete process improves the efficiency of the excavation as well as subsequent analysis.

For each 3D model presented in this article a series of photos were taken over the entire archaeological site. The number of photos ranged from 300 to 700 depending on the area of the underlying site and the required level of detail. Photos were then processed automatically using the PHOV Mementify online service and analyzed manually using the Meshlab tool. Photos were not pre-processed in any way prior to processing. The resulting 3D models were manually cleaned by removing redundant regions.

D. Comparison of structured light and photogrammetry

For comparison with photogrammetry, we used an Artec MHT structured light 3D scanner. Along with object shape, the 3D scanner also captures texture information. It is ideal for smaller archaeological artifacts with rough surfaces. The whole process of data registration is automated and fast. The 3D models obtained with Artec MHT now serve to us as a baseline for point accuracy, speed of data acquisition and ease of use.

We are performing extensive tests to compare White Light Scanning and photogrammetry on the ground and under water for 3D model creation (Fig. 13). Preliminary results show that in most situations photogrammetry produces better results in all aspects of 3D modeling as well as authentically reproducing color and texturing of the object although the accuracy of a single frame from a structured light scanner is more accurate (error < 0.1mm). But due to image registration and conversion of data to a rectangular grid errors start to accumulate in structured light 3D models when scanning larger objects [27].

Turbidity of water and the resulting scattering of light rays had an adverse effect on the accuracy of 3D models of underwater objects reconstructed with photogrammetrical methods as can be seen in Fig. 13. We are studying how turbidity and errors in the 3D model are related so that a practicing archeologist could get an estimate of the possible maximal accuracy of 3D models in a given underwater environment before the actual documentation starts.

E. Software for Visualisation and Analysis

An archaeological 3D modeling software should combine two equally important work perspectives: (1) model analysis, and (2) model visualization. Model analysis perspective has an important role in understanding the findings. There are many procedures which can be automated or semi-automated: (1) model segmentation, (2) distance and volume measures over the model and its segments, (3) creating model-plane intersections for detailed analysis of model features, (4) connecting model to a Geographical Information System, and (5) automatic classification using open databases.

The visualization perspective is in many cases strongly connected to model analysis. It should not include only 3D model rendering, but also visualizing any additional information related to the model: multimedia (detail site images and videos), GIS data, notes and spreadsheets etc. This perspective can help archaeologists get a detailed overview of the site, the findings, the procedure and the whole context. It can also serve for presentation purposes. Allen et. al [28] have recognized these needs and designed a virtual reality in which users can inspect the site and all of its related information.

Additional functionality such as model editing (transformations, scaling etc.), model alignment and photogrammetry without any third-party intermediaries can also automate many time-consuming routines and help archaeologists focus their time on more important tasks.

IV. Benefits of Change in Underwater Heritage Recording Methodology

The advantages of modern measurement methods and technology, which is getting financially accessible, and continuous improvements of open source software solutions are manyfold.

A. Accuracy

Analog documentation was mainly recorded with single measurements and therefore systematic errors or mistakes in the recordings could not be corrected during the subsequent analysis 12. These problems were mitigated only in the last decades by introducing triangulation techniques which enables the creation of 3D documentation consisting of sparse morphological properties combined with 2D photographs of surfaces. Such documentation enabled a rough 3D reconstruction or at least correct basic orthographic views [15]. The latest 3D recording technology enables in principle very accurate documentation, with errors on the order of milimeters, but the influence of the turbidity of water on the accuracy of 3D models still needs to be quantified.

B. Increased safety in dive operations

The safety of divers during underwater research of cultural heritage is of utmost importance. Therefore, research should be organized in such a way that the hours spent underwater should be kept at a minimum. The latest technological advances enable enormous time savings during the documentation of an underwater archeological site. For comparison, we can take the project of documenting the Roman barge in Sinja Gorica (see II-C) which lies at the depth of 3m. For producing analog documentation which would consist of a 2D floor plan, 2 or 3 cross sections and 2 or 3 longitudinal sections, we would need about 25–30 diving hours.

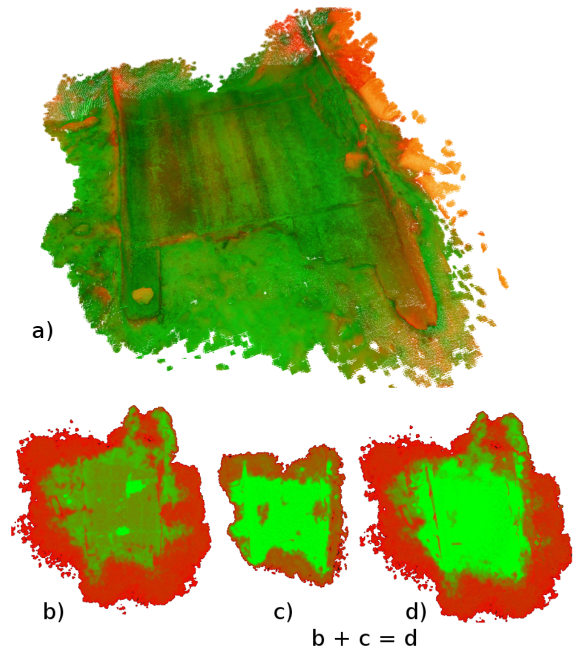

Fig. 14. Comparison of two different photogrammetric reconstructions of the Roman barge at Sinja Gorica. (Analysis: Mitja Pugelj, photo: Rok Kovačič, 3D model: Gregor Berginc, processing by PHOV, 3D view by Meshlab)

Taking photographs for the photogrammetric reconstruction, for each set or phase in the excavation we needed about 900 photographs, took us only about 3–4 diving hours. A comparison of the reconstructed 3D model in two different excavation phases is shown in Fig.14. By comparing these 3D reconstructions from different sets of photographs we study also the accuracy of the obtained models.

C. Efficiency and Cost

A smaller amount of diving hours results also in smaller cost of research since, in general, the cost of diving operations is much higher than the cost of post processing analysis which can be done on the ground. The correlation between quality of documentation and the cost to record it, is therefore incomparable with this ratio in the past.

V. Conclusions and Future work

New 3D shape recording technology using active scanners or series of photographs for photogrammetric reconstruction, new and better open source software for 3D reconstruction, modeling and analysis are a breakthrough in research of underwater cultural heritage since they offer so far unsurpassed accuracy of primary documentation and greater safety during underwater activities due to shorter time spent underwater.

Beside observing attractive virtual models the benefits of captured 3D data are abundant. A 3D model enables simulated virtual inspection of documented surfaces or objects and their analysis almost as satisfactory as in situ. Due to the morphological properties of 3D data point clouds which represent the actual state of the artifacts, further analysis of the 3D models is possible which would even not be possible to perform on actual archeological sites. One can systematically study, segment or classify features that could be missed on the actual physical artifacts due to time constraints. Special consideration should be directed also to the archival durability of digital archeological documentation for further analysis, interpretation, promotion and sustainable future use.

Within the next couple of years, photogrammetric methods will continue to improve the level of detail, both geometry and texture, captured in resulting models and further eliminate some of the main limitations of purely photo-based methods, such as a texture and light dependance. However, a combination of 3D scanning and photogrammetry should still surpass both methods individually due to characteristics of regions reconstructed using these methods.

We envision (semi-)automatic segmentation of 3D models as one of the most important tools allowing archaeologists performing analysis of 3D models based on the natural structure of the site [29]. Context-aware measuring tools, surface analysis and sketch generators would allow further improvements in the understanding of the underwater archaeological sites.

We will continue with the studies of how the capture of photographs for 3D reconstruction and modeling can be rationalized and optimized. We study the minimal requirements such as the number of photographs and the amount of overlap between them, how the focal length of lens, the size and resolution of the imaging sensor and turbidity of water influence the accuracy of the 3D model? We are developing software tools for the analysis of such data, such as segmentation of the data into parts, integration of 3D measurements from different sets of photographs and also from different sensors etc. Finally, even with the examples presented in this paper, a need for a standard methodology arose. Therefore, we will focus also on the standardization of the data acquisition process guaranteeing stable results across a multitude of different scenes and objects.

ACKNOWLEDGMENT

This work was supported by the Slovenian Research Agency, research program Computer Vision (P2-0214), the Ministry of Culture of the Republic of Slovenia and the City Museum of Ljubljana.

REFERENCES

[1] F. G. Bass, *Archaeology Under Water*. New York: Praeger, 1966.

[2] P. Trockmorton, "Oldest known shipwreck yields bronze age cargo," *National Geographic*, vol. 121, no. 5, pp. 696–671, 1962.

[3] ——, *Diving for Treasure*. London: Thames and Hudson, 1977.

[4] B. Bačić and J. Štirn, *Antični brodolom v Savudriji*. Arheološki muzej Istre in Center za podvodna raziskovanja SRS, 1963.

[5] D. Vrsalović, "Arheološka istraživanja u podmorju istočnog Jadrana: prilog poznavanju trgovačkih plovnih putova i privrednih prilika na Jadranu u antici," Ph.D. dissertation, University of Zagreb, 1979.

[6] E. Boltin-Tome, "Pregled dosedanjih hidroarheoloških raziskav ob slovenski istrski obali," in *Pitanja istraživanja i zaštite hidroarheoloških spomenika u podmorju istočne obale Jadrana. Prvo međurepubličko savjetovanje*, 1975, pp. 123–132.

[7] A. Gaspari, "Divers of the royal and imperial navy in Vrhnika in 1884," *Argo*, vol. 44, no. 2, pp. 48–52, 2001.

[8] A. Gaspari and M. Erič, "Minimalni standardi podvodnih arheoloških raziskav: izhodišča in smernice," Ministry of Culture Republic of Slovenia, Ljubljana, Tech. Rep., 2010.

[9] E. Diamanti, A. Georgopoulos, and F. Vlachaki, "Geometric documentation of underwater archaeological sites," in *XIII CIPA International Symposium, Prague*, 2011.

[10] S. Glusčević, "The Roman shipwreck from the 1st century AD at Grebeni by the island of Silba (preliminary results)," *Adriatica maritima mediterranea*, vol. 6, pp. 69–87, 2009.

[11] S. Poglajen and P. Slavec, "Underwater cultural heritage and palaeoenvironment from the Slovenian sea as revealed by hydrographic and geophysical data," in *Submerged Past: Archaeology of the aquatic environments and underwater cultural heritage exploring in Slovenia*, A. Gaspari and M. Erič, Eds. Radovljica: Didakta, 2012, pp. 81–90.

[12] M. Erič, S. Poglajen, and A. Gaspari, "Registering cultural heritage in the territorial sea of the Republic of Slovenija and the perspectives on its management," in *Submerged Past: Archaeology of the aquatic environments and underwater cultural heritage exploring in Slovenia*, A. Gaspari and M. Erič, Eds. Radovljica: Didakta, 2012, pp. 167–176.

[13] M. Erič, "Documenting a Roman vessel at Sinja Gorica," in *Submerged Heritage*, ser. Yearbook of the International Centre for Underwater Archaeology in Zadar, L. Bekić, Ed., 2012, vol. 2, pp. 58–65.

[14] M. Krese and A. Hodalič, "Potopljena ladja," *National Geographic, Slovenija*, pp. 126–131, Januar 2013.

[15] P. Holt, "An assessment of quality in underwater archaeological surveys using tape measurements," *International Journal of Nautical Archaeology*, vol. 32, no. 2, pp. 246–251, 2003.

[16] "Site recorder 4, data management software," www.3hconsulting.com, 2013, online; accessed 10-June-2013.

[17] I. Mihajlović, "Antique shipwreck with sarcophagi near Sutivan on the island of Brač)," *Histria Antiqua*, vol. 21, pp. 649–655, 2012.

[18] J. Green, S. Matthews, and T. Turanli, "Underwater archaeological surveying using photomodeler, virtualmapper: different applications for different problems," *International Journal of Nautical Archaeology*, vol. 31, no. 2, pp. 283–292, 2002.

[19] P. Drap, "Underwater photogrammetry for archaeology," in *Special Applications of Photogrammetry*, D. C. da Silva, Ed. InTech, 2012, pp. 111–136.

[20] F. Remondino, "Heritage recording and 3D modeling with photogrammetry and 3D scanning," *Remote Sensing*, vol. 3, no. 6, pp. 1104–1138, 2011.

[21] Z.-y. Wang, D.-p. Li, and Y. Shan, "Image distortion analysis for underwater laser scanning system," in *OCEANS, 2005. Proceedings of MTS/IEEE*. IEEE, 2005, pp. 2200–2203.

[22] F. Bruno, G. Bianco, M. Muzzupappa, S. Barone, and A. Razionale, "Experimentation of structured light and stereo vision for underwater 3D reconstruction," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 66, no. 4, pp. 508–518, 2011.

[23] C. Roman, G. Inglis, and J. Rutter, "Application of structured light imaging for high resolution mapping of underwater archaeological sites," in *OCEANS 2010 IEEE-Sydney*. IEEE, 2010, pp. 1–9.

[24] D. G. Lowe, "Distinctive image features from scale-invariant keypoints," *International Journal of Computer Vision*, vol. 60, no. 2, pp. 91–110, 2004.

[25] N. Snavely, I. Simon, M. Goesele, R. Szeliski, and S. M. Seitz, "Scene reconstruction and visualization from community photo collections," *Proceedings of the IEEE*, vol. 98, no. 8, pp. 1370–1390, 2010.

[26] Y. Furukawa and J. Ponce, "Accurate, dense, and robust multiview stereopsis," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 32, no. 8, pp. 1362–1376, 2010.

[27] Ž. Stopinšek, "Applicability of 3D scanners in cultural heritage," Faculty of Computer and Information Science, University of Ljubljana, Dipl. thesis, 2012.

[28] P. Allen, S. Feiner, A. Troccoli, H. Benko, E. Ishak, and B. Smith, "Seeing into the past: Creating a 3D modeling pipeline for archaeological visualization," in *3D Data Processing, Visualization and Transmission, 2004. 3DPVT 2004. Proceedings. 2nd International Symposium on*. IEEE, 2004, pp. 751–758.

[29] A. Jaklič, A. Leonardis, and F. Solina, *Segmentation and recovery of superquadrics*. Springer, 2010.