CARTAGENA 2014
IKUWA V

Actas del V Congreso Internacional
de Arqueología Subacuática
Un patrimonio para la humanidad
Cartagena, 15-18 de octubre de 2014

Proceedings of the 5th International
Congress on Underwater Archaeology
A heritage for mankind
Cartagena, October 15th-18th, 2014

Akten des 5. Internationalen
Kongress für Unterwasserarchäologie
Ein Erbe für die Menschheit
Cartagena, 15. bis 19. Oktober 2014

GOBIERNO DE ESPAÑA   MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

ARQVA   Museo Nacional de Arqueología Subacuática

Successful use of temporary underwater 3D documenting methodology:
Early Roman barge from Ljubljanica river, Slovenia

Uso exitoso de la metodología de documentación 3D subacuática: una embarcación romana del río Ljubljanica, Eslovenia

Miran Erič

Institute for the Protection of Cultural Heritage of Slovenia, Ljubljana, Slovenia

miran.eric@guest.arnes.si

Gregor Berginc

Tretja dimenzija, Ltd. Ljubljana, Slovenia

gregor.berginc@3dimenzija.si

Rok Kovačič

Golden Light Photography - Kult Ltd, Ljubljana, Slovenia

rokkov@gmail.com

Mitja Pugelj

Comland Ltd, Ljubljana, Slovenia

Computer Vision Laboratory, Faculty of computer and Information Science

University of Ljubljana, Ljubljana, Slovenia

mitja.pugelj@gmail.com

Franc Solina

Computer Vision Laboratory, Faculty of computer and Information Science

University of Ljubljana, Ljubljana, Slovenia

franc.solina@fri.uni-lj.si

Miran Erič, Gregor Berginc, Rok Kovačič, Mitja Pugelj, Franc Solina

Abstract: After a long period of learning photogrammetric methodologies for documentation of underwater archaeological sites, which we started in eastern Adriatic 15 years ago on the island of Silba, we finally got an opportunity to replace old site documenting methods based on measuring with contemporary possibilities offered by rapidly progressive development of 3D documentation. Despite our desire to carry out simultaneously also the previous standard documentation procedure using tape measurement to demonstrate the many advantages of using 3D documentation, due to the lack of time and adverse weather conditions it had to be abandoned. On this early Roman barge site in river Ljubljanica we demonstrate and prove that the new methodology of documenting underwater sites extremely facilitates archeological fieldwork. As it was expected, it turned out that contemporary approaches are much cheaper due to significantly shorter underwater data acquisition, more accurate documentation and due to shorter diving times required for data acquisition also greatly increased safety.

Key words: Photogrammetry, 3D modeling, comparative analysis, early Roman barge, river Ljubljanica.

Resumen: después de un largo periodo de aprendizaje de metodologías fotogramétricas para la documentación de sitios arqueológicos subacuáticos, que iniciamos en la isla de Silba (Adriático Este) hace 15 años, finalmente nos dieron la oportunidad de reemplazar los viejos métodos de documentación –basados en mediciones– por las nuevas posibilidades de documentación 3D. Pretendíamos realizar al mismo tiempo ambos procedimientos para demostrar las muchas ventajas del uso de documentación 3D, pero no pudo ser por falta de tiempo y condiciones meteorológicas adversas. En esta barcaza romana ubicada en el río Ljubljanica, demostramos y probamos que la nueva metodología para documentar yacimientos subacuáticos facilita extremadamente el trabajo de campo arqueológico. Resultó que era un procedimiento más barato debido a que la adquisición de datos bajo el agua es más rápida, la documentación más precisa y además en gran medida se aumenta la seguridad al necesitar tiempos de buceo más cortos para la adquisición de datos.

Palabras clave: fotogrametría, modelado 3D, análisis comparativo, barcaza fluvial romana, río Ljubljanica.
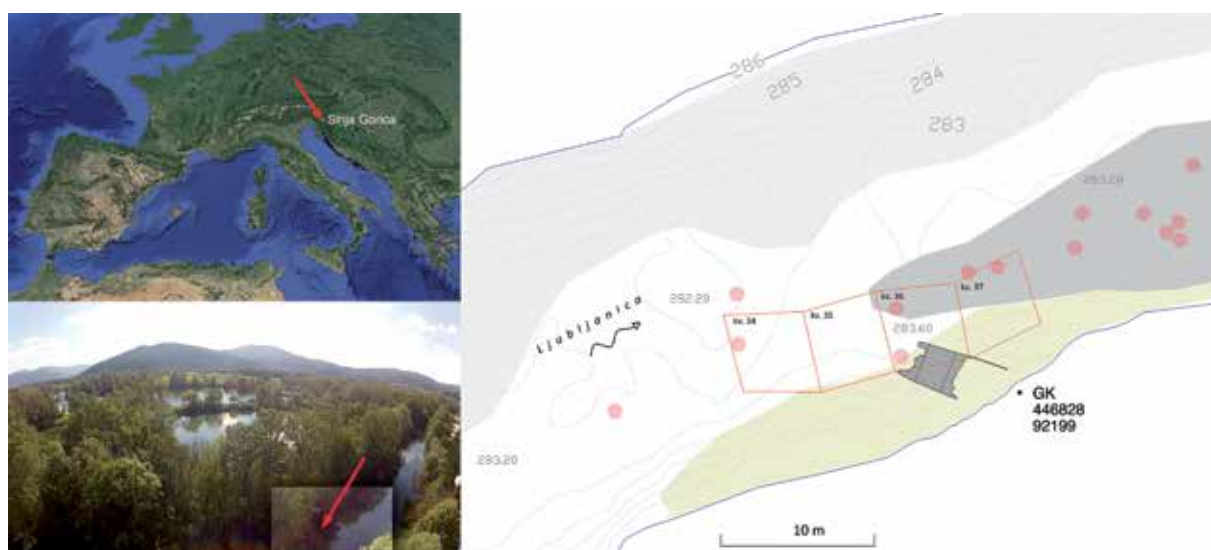

Figure 1. [*Right*] Position of explored part of early Roman barge in river Ljubljanica. Red squares shows the area of intensive underwater survey and red dots are positions of other findings. [*Left bottom*] Aerial landscape view of the site. View towards the south with the Javorč hill and Ljubljanski vrh hill from right back. (GoPro clip: Aleš Jaklič).

Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

261

Introduction

A preventive underwater survey in September 2008 of the river bed of Ljubljanica near Sinja Gorica (Vrhnika, Slovenia) revealed remains of a vessel (Fig. 1). A closer inspection of the exposed cross-section of the vessel indicated that the vessel could be a more than 16 m long barge with flat bottom and nearly vertical side planks coupled with iron clamps. A preliminary radiocarbon analysis of the wood indicated that it was built and used ca. 2000 years ago, when the nearby *vicus* Nauportus was controlled by important Aquileian merchant families and played also an important role in military shifts and in passing supplies.

Recently, reliable and fast open source photogrammetric software solutions for acquiring, processing, analysis and display of 3D layers of data appeared. These tools are of enormous help in modernizing the methodology of underwater archeological surveying to get better and much more accurate results that in the end result in better protection of underwater cultural heritage. These tools were tested for the first time in Slovenia on the site of the Roman barge in river Ljubljanica at Sinja Gorica in October 2012. Data for the photogrammetric reconstruction was collected using underwater photography. The reconstructed 3D point cloud set then served for 3D modelling.

The Roman barge that had no cargo or other objects was first cleaned of recent sediments. Then the shape of the visible part of the barge was documented using in parallel manual survey and photogrammetry. The 3D model derived from the photogrammetric reconstruction was much more accurate and informative than the manually drawn documentation that contains 2D floor and side views, 2D cross sections and detailed drawings of individual construction elements. The 3D model enables almost as detailed examination and analysis of the vessel as observation *in situ*. Even archive photographs of extremely good quality, which are still needed, cannot match the 3D model.

Methodology

Contemporary photogrammetric methodology in underwater archaeology has a long history (Drap *et alii*, 2013), on the eastern coast of the Adriatic Sea as well (Erič *et alii*, 2013: 282, fig. 3-4). Its beginnings had the same limitations as photogrammetry on dry land conducted by remote sensing and GIS studies used primarily for geodetic purposes. Taking of underwater photographs in a manner to assure a precise alignment of photographs used to be a lengthy process, which was followed in the laboratory by marking corresponding points on stereo image pairs. This made underwater photogrammetric documentation more expensive than the manual or classic documentation, both because of the extensive underwater work and of the painstaking laboratory processing. Because of the limitations of time and money, the amount of photogrammetric measurements was, in the past, never sufficient for them alone to form the basis of field documentation and drawings of small finds and thus completely replace classic documentation.

Modern computer-based photogrammetric methods and tools, however, allow enough data to be captured to create a range or 3D images consisting of a dense point cloud where each point has all three coordinates. These image based 3D modelling methods are gaining a foothold also in land archeology (De Reu *et alii*, 2014).

Today, underwater photogrammetric collection of data is not only much more accurate and faster than classic documentation, but because of the shorter diving time necessary for taking photographs also faster, less expensive and safer. Of all the methods of underwater 3D

documentation, photogrammetry has become the most useful. To document the Early Roman barge from Sinja Gorica, we used a photogrammetric recording method to obtain a 3D model for the first time in Slovenia. The photogrammetric reconstruction from a set of photographs is completely automatic and consists of the following stages: identification of discriminative points in individual photographs, search of stable correspondence among these points in different photographs, automatic calibration of a set of photographs, construction of a dense cloud of 3D points that best describes the information available on input photographs and finally creation of a triangulated textured network.

Traditionally, photogrammetry consisted of two phases, photographic data acquisition, which can be performed very efficiently, and manual registration of photographs done on a computer, requiring tremendous effort by an experienced archaeologist. In order to ascertain whether the data are reliable photogrammetric 3D documentation we conducted also a comparative analysis of the two models recorded in two different days.

Acquisition data by photography

For the purposes of underwater 3D photogrammetry and acquiring a high detailed 3D model of the site, it is important to use proper equipment. It is true, that in ideal conditions you can work with almost any decent digital capturing device that is available to you, but it is always wise to get the most data out of the site and collect it with the best equipment one can get. There are many reasons to do so: (I.) you can document underwater and other sites in demanding, often low light and low visibility conditions in high detail. (II.) With the right equipment the workflow is smooth, dive times are shortened and best results are achieved. (III.) High detail images are important for later off-field analysis and future 3D modeling, when the algorithms will get even better. (IV.) Only high detail images, with low noise and no lens distortion will produce the best 3D models with the densest 3D point cloud. Currently (January 2015), we use a full frame (FX) digital SLR camera with 36MP with very low noise even at high ISO. At the time of documenting the Roman barge (October 2012) we used a cropped (DX) digital SLR camera with 12MP, with sharp lenses in a heavy-duty full aluminum casing. For 3D documentation no camera-mounted strobes can be used. Due to computing hardware limitations we processed all the photo sets in 1360 × 2050 pixel resolution, although we had captured them at 2850 × 4290 pixels.

For archeological field work and underwater documentation heavy duty and sturdy equipment is needed. Demanding environmental conditions can obstruct the work and push the limits of the camera. With low-end and mid-level cameras, the safety of divers and accuracy of 3D models will be in question. To shorten the time of the dive and keep accurate and valid data for further processing, high-end fast performing gear should be used. Before capturing any data one must be sure to use proper settings. If possible, use aperture f8.0 to f11.0, shortest possible shutter times no slower than 1/60 and lowest possible ISO not exceeding ISO 800 on DX or ISO 1500 on FX cameras.

These are the best settings for highest possible data input. In order to get enough light on the sensor when the conditions are not good, it is necessary to make compromises.

Opening the aperture will result in a shallow depth of field (DOF) making it impossible for the 3D software to determine corresponding points in image pairs and produce a dense 3D point cloud. Since DX cameras, which have a smaller sensor, have a greater DOF, it is possible to adjust the aperture for a level or two lower.

263

Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

Prolonging the shutter time will result in shaken and blurry images, which will reduce the accuracy of the model and the number of stitching points. So the only option left is a higher ISO setting what will result in more noise. Some smaller noise corrections can be done in post processing without a great loss of information. Depending on the type of the camera, ISO may be increased, but it is better for further processing to remain as low as possible.

Five 3D models (a-e) were produced in different phases of the excavation. The first model (a) was made with a 10 mm fish-eye lens (see figure 2 for more about camera settings). It covered a wide area in a single frame, but had strong lens distortions which pushed the Mementify©PHOV software to several days of computing before a cloud of 3D points emerged. The second and the third set were captured with the same lens but tested and processed with a different algorithm, which produced a lower detail model (b and c). The fourth set was captured with a 12 mm wide-angle lens, which despite lower DOF images, produced a high detail 3D model (d) with more than 3 million faces. The fifth set was captured in the same manner and lower DOF, but still produced a 3D model (e) with 3.3 million faces.

Set	Model	Date	Day	DT	Nr.Sh	Method of sequence shots	Lens	F	t	ISO	Faces
1	A	1.10.2012	2	4'	55	6 lines	10mm	8.0	1/50	640	0.12M
2	/	2.10.2012	3	20'	334	10 lines + 6 rows	10mm	4.0	1/50	640	
3+	B	4.10.2012	5	30'	57	3 side lines	10mm	7.1	1/50	800	0.2M
3	C	4.10.2012	5	30'	450	10 lines + 7 rows	10mm	7.1	1/50	800	0.8M
4	/	9.10.2012	9	20'	912	9 lines + 8 rows	12mm	6.3	1/50	800	
4+	/	9.10.2012	9	5'	205	Detailed line	12mm	6.3	1/50	800	
5	/	11.10.2012	10	20'	586	6 lines + 9 rows	12mm	7.1	1/50	800	
5+	/	11.10.2012	10	15'	702	Detailed line	12mm	7.1	1/50	800	
6	/	15.10.2012	12	2'	39	Planar photomosaic	12mm	6.3	1/50	640	
6+	D	15.10.2012	12	10'	314	5 lines + 5 rows	12mm	6.3	1/50	640	3.03M
6++	/	15.10.2012	12	10'	578	Detailed 8 lines + detailed 7 rows	12mm	6.3	1/50	640	
7	/	22.10.2012	14	6'	278	Detailed line	12mm	5.6	1/50	800	
7+	E	22.10.2012	14	10'	502	8 lines + 7 rows	12mm	5.6	1/50	800	3.3M

Figure. 2 Table presents the ID number and names of 3D models (Set #, Model), dates and sequential working day numbers, dive times (DT), number of shots (Nr. Sh) captured during the dive, methods of sequencing the shots, camera settings (F – focus, t – time and ISO - sensitivity) and the number of faces in the 3D model in millions (M).

The taking of photographs for all sets took place in murky water and at low light conditions, so it was very difficult to obtain data of necessary quality for the 3D model procesing

Figure 3. In murky water and low light conditions diver prepares the vessel for the study and documentation of ship construction technology and 3D modeling (GoPro clip: Rok Kovačič).

(Fig. 3). Because of the site conditions, the equipment was pushed to the limits. The shooting settings were set at 1/50s and F as low as 4.0 but most of the time F was 6.3, which is still a bit low for perfect results. Underwater visibility varied from 1 m to 2 m at best. Still, in these difficult circumstances we were able to document each phase of the excavation in detail and in under 30 minutes, which is an amazing shortening of dive time and great tool for later analysis and measurements.

Groups of purposely taken images from different viewpoints allow the reconstruction of more or less complete 3D models. All the constraints regarding the accurate placement of cameras thus fall off. The camera can be held in the hand without any additional equipment, one must only capture a large enough set of photographs with a roughly 75% pairwise overlap.

Photogrammetric 3D modeling with Mementify©PHOV Software

Powerful computer algorithms and software applications already exist enabling 3D model reconstruction of scenery from digital photographs as well as, due to significant improvements to digital sensors in recent cameras, from high-definition video recordings. Compared to the classic methods of documentation, such as laser scanning and manual drawing, this approach offers significant simplification of the entire process of capturing and modeling, thus making it increasingly more interesting and useful even in archaeological research.

265

Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

The service used in this paper, Mementify©PHOV, is based on a series of phases analysing input photographs, determining the relative positions and orientations of photographs, and then building a triangulated mesh of a dense 3D model. The first phase of the process uses a feature detector to extract distinct features from input photographs, and looks for matches thereof. Matching of detected features, i.e. finding correspondences between photographs, is performed by a stochastic algorithm comparing arbitrary subsets of features found in two different photographs to minimise the effect of mismatches, i.e. pairs of features that should not be matched. Distinctiveness of features and the expresive power of corresponding feature descriptors is required for the matching algorithm. For the models presented in this paper, SIFT (Scale Invariant Feature Transform) algorithm (Lowe, 2004) have been chosen due to its ability to match features even under significant transformations, such as scale and orientation, within photographs. Stable correspondences are used in the second phase of the process extracting relations between subjected photographs based on the Structure from Motion (SfM) algorithm Bundler (Snavely *et alii*, 2010). The algorithm seeks the configuration of cameras minimizing the error of applying perspective projection to detected 3D points when compared to 2D points found in photographs. The SfM algorithm incrementally increases the number of used photographs and updates the configuration in each step of the process to build the final representation of the scene. Photographs that cannot be matched sufficiently to others, or those that introduce a significant amount of error are rejected. Although the resulting camera configuration also details intrinsic parameters of cameras, we have found that unwarping input photos significantly improves the end results. Unwarping is based on a manual calibration of the camera. The so updated camera configuration forms the input to the next phase of the reconstruction process building a dense point-cloud representation of the scene based on the Patch-based Multi-View Stereo (PMVS) algorithm (Furukawa/Ponce, 2010), and the triangulated approximation of a surface using Poisson surface reconstruction algorithm (Kazhdan *et alii*, 2006) building a watertight model, i.e. the manifold without holes. The last phase of the automated 3D reconstruction uses camera configurations to project input photographs onto the reconstructed mesh and producing color (texture) of the mesh. Parts of the resulting mesh that are not covered by a significant amount of input photographs are also removed in this phase detailing only the part of the scene that has been captured properly by input photographs.

Resulting models have been analysed and further distilled using the MeshLab, a tool for 3D mesh visualisation, processing and editing developed with the support of the 3D-CoForm project, freely available for all major operating systems. The power of the MeshLab lies in its ability to visualise and manipulate large 3D models containing several millions of vertices. It also comes with a large number of predefined filters based on extensive research in the field of computer vision facilitating analysis and automatic mesh corrections.

Although models reconstructed by the aforementioned approach offer an important novel analytical tool, we see numerous potential improvements in the archaeological workflow, in particular, for the post-processing of resulting models. Examples of such tools are (semi-)automatic segmentation of 3D models allowing archaeologists separating 3D models into distinct sub-parts performing analysis to each individual part, e.g., based on the work of Solina *et al.* (Solina/Baycsy, 1990; Jaklič/Leonardis/Solina, 2000), context-aware measuring tools, surface analysis and sketch generators.

Analysing of different 3D models of the barge

When one is faced with more than one model of the same object, there is a question of how to compare and evaluate different models. This is usually done visually by a human operator. The model that looks more complete and visually appealing is selected as a better one. However, the

approach is not objective and not useful if one would need to compare two models in an automated chain of processing.

The problem of comparing two different models in quality is an easy task only if ground-truth is available (a high-quality model obtained in ideal environment, usually in artificial setup), which is in field archeology normally not the case. One way to do the comparison is by comparing inherent properties of each model: number of points in the point cloud, number of faces in the mesh model, absolute point/vertex density, point density variance, number of outliers, fractal dimension, edge and plane smoothness, number and size of «holes» in the point cloud, etc. By comparing and combining this metrics, it is possible to construct a heuristic distance function for comparing two models.

However, in practice, especially in underwater archaeology, the situation is more complex due to the changing environment and challenging model reconstruction. If an object is partially covered with other artefacts or mud, it is impossible to automatically determine if the measured «noise» is there due to the poor model as such or to artefacts on the actual surface of the object.

Due to the nature of the problem at hand, we have decided to evaluate different models using a semi-automated approach. First, the two models to be compared are scaled to the same scale and aligned. Next, a 2D heat map is computed in the following way: a 2D plane is placed in parallel to the river bed. The distance between the two models in the axis perpendicular to this place is computed and stored in a heat map (a colour represents the distance between models). This heat map is then mapped to a 3D space (where both point clouds are merged together for visualization). This gives a 3D representation of the difference of two models as seen in figure 7. Using this representation an educated user can easily see where the two models differ, evaluate and understand the difference and provide a better assessment on the quality of both models. Although this approach does not provide a clear metric for selecting a better model, it gives a better insight into their quality which is not obtainable merely by visual inspection.

Case: Early Roman barge from river Ljubljanica

In advance of maintenance work involving the consolidation of the right bank of the river Ljubljanica, the Underwater Archaeology Division (hereinafter UAD) of the Institute for the Protection of Cultural Heritage of Slovenia (hereinafter IPCHS) surveyed in 2008 a 200m long section of the river at Sinja Gorica (Erič/Gaspari, 2009). The intensive underwater survey of the potentially endangered riverbed (Heritage Register Number 11420) along plots Nos. 1100, 1125, and 1865/1, cadastral municipality Verd, was performed under the auspices of the ZVKDS (Fig. 1; *left*).

Field work

The survey of 44 square grids revealed 2500 small finds, mostly fragments of prehistoric, Roman, medieval, early modern, as well as modern pottery and construction materials. Noteworthy finds included an Early Roman Aucissa fibula, an undated iron ingot weighing roughly 10 kg and a wooden Palaeolithic point, presumably part of a 45 000-year-old hunting weapon (Gaspari/Erič/Odar, 2011; 2012). In the easternmost part of the surveyed area, along Grid Squares 35 and 36, the survey also revealed the remains of a wooden barge at a depth of 2.5 m under mean water surface, at an absolute altitude of 284.11 m and GK coordinates of y 446827, x 92200. Its remains, consisting of left and right chine-girders, five planks of the flat bottom and iron clamps, are lying horizontally and continue at an angle into the sediments of the right river bank. Probably also belonging to the vessel are the 15 iron clamps and two wrought nails found scattered in close

267

Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

vicinity. The survey determined the approximate width between the chine-girders at 2.4 m, which, together with the obtained radiocarbon age, pointed to a 12 to 15 m long barge from the closing decades BC or the early decades AD.

In May of 2009, the IPCHS UAD conducted non invasive documentation of the barge also aimed at establishing the state of its wooden remains eight months after discovery. Documentation was performed by M. Erič and R. Kovačič, authors of this article (Erič, 2009). These were found to be exposed to water flow erosion due to the maintenance of the right river bank and therefore exceedingly endangered.

On the initiative of the IPCHS, the Slovenian Ministry of Education, Science, Culture and Sports in October 2012 provided intervention funds for documenting the barge and transferring it to the state depository for waterlogged wood which was in preparation in the nearby ponds. The task of the ZVKDS SPA research team was thus to document the remains of the vessel and to transfer them to the depository. The team was made up of several groups of collaborators and advisers. A considerable contribution to the fieldwork was provided also by donations by the local community. It took eleven members of the field team and several assistants 150 diving hours in 23 days to document the wreck and 36 hours to prepare the wooden support construction of the depository. The barge without cargo or any other objects identifiable as boat equipment was cleaned of recent sediments in the length of 4.2 m (Fig. 1; *right*). On the eastern side of the barge, the side plank could be followed for another 3 m, but was not documented due to safety concerns (Erič *et alii*, 2014).

The surviving part of the barge was substantially larger than expected and investigations showed that the wood is poorly preserved. Consequently, the lifting of the barge out of water and its conservation would be highly demanding and very costly. Therefore, the initial plan to transfer the barge to the depository for waterlogged wood was abandoned (Čufar/Merela/Erič, 2014). We decided for protection *in situ;* the cleared part of the barge was documented and afterwards protected with a thin layer of silt and sand, which was covered first with a degradable anti-flood net made of jute and then with sandbags.

Why we decided to use the methodology of 3D documentation?

In recent decades we have devoted in Slovenia a lot of time and attention to understand and develop methods for collecting and acquiring data on underwater archaeological sites. These efforts are illustrated in several articles on underwater archaeological sites in Slovenia (e.g. Gaspari, 2015; Erič, 2015).

Our first experience with the process of 3D documentation and underwater data acquisition on an archaeological site is from 2001. This was during fieldwork research of a Roman shipwreck from the 1st century AD at the cliffs of Grebeni near the island of Silba, led by Smiljan Gluščević from the Archaeological Museum of Zadar (Gluščević, 2009; Gaspari/Erič, 2001; Erič *et alii*, 2013: 282; fig. 3-4).

During this period our understanding of the benefits of 3D documentation in underwater archeology has evolved, as well as the realization that a change in underwater recording methodology was necessary to reap these benefits. Instead of producing first two dimensional plans and documentation to gain an understanding of a site in three dimensions, the new image based 3D modeling does not require any intermediate transmission between 2D and 3D. Further, these new automatic image based 3D modeling methods are financially accessible and open source solutions exist.

Based on our experience in underwater archeology, we are particularly impressed by the advantages in accuracy, financial affordability and increased safety at underwater field work.

1. Analog documentation was mainly recorded using single measurements and therefore systematic errors or mistakes in the recordings could not be corrected during subsequent analysis. 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 (Holt, 2003). The latest image based 3D recording technology enables in principle very accurate documentation, with errors on the order of millimeters, however, adverse environmental conditions such as the turbidity of water influence the recording of images and subsequently the accuracy of 3D models.

2. A smaller amount of diving hours results also in smaller cost of field 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.

3. The safety of divers during underwater field work 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 site recording. To illustrate this large difference, we can use the project of documenting the Late Roman Sarcophagi Shipwreck which lies at the depth of 30 m conducted by Igor Mihajlović from the Department for Underwater Archaeology, Croatian Conservation Institute (Mihajlović, 2013). To produce the analog documentation which consists of a 2D floor plan, 2 or 3 cross sections and 2 or 3 longitudinal sections, about 25-30 diving hours were required. The taking of photographs for the photogrammetric reconstruction, for a single set or phase in the excavation about 700 photographs are needed, required less than one (1) diving hour.

Results and discussion

3D models of investigated part of barge

In order to test the image based 3D modeling we first performed a series of rapid tests, increasing the number of photos used in the reconstruction and proportionally increasing the area covered by the set of photos (Fig. 4a, 4b, 4c). The main reason for experiments was to analyse the water conditions and determine whether the capturing process is well defined and executed by the photographer under water. The top part of figure 4 (a-c) depicts resulting 3D models and the estimated area. Although the exact shape in figure 3a is hard to see, it can be clearly seen that with a set of 55 properly aligned photographs it is possible to cover a part of the model and extend that to the entire area (Fig. 4b, 4c). Having confirmed the approach and the methodology two series of photographs were captured in similar lighting conditions (Fig. 4d, 4e) after the site has been cleansed. The 3D reconstruction of the latter models took approximately 6 hours on a parallel computer system and approx. 30 hours on a single processor. Based on the optimised solution we could improve the capturing process and focus on parts that have not been sufficiently covered in the first session.

Figure 5 depicts different stages of the reconstruction process described in the subepigraph «Photogrammetric 3D modeling with MementifycPHOV Software». A dense point cloud is displayed in (a) providing an excellent overview of the entire scene as seen by captured photographs. Areas in the middle are covered almost completely while those on the boundaries are
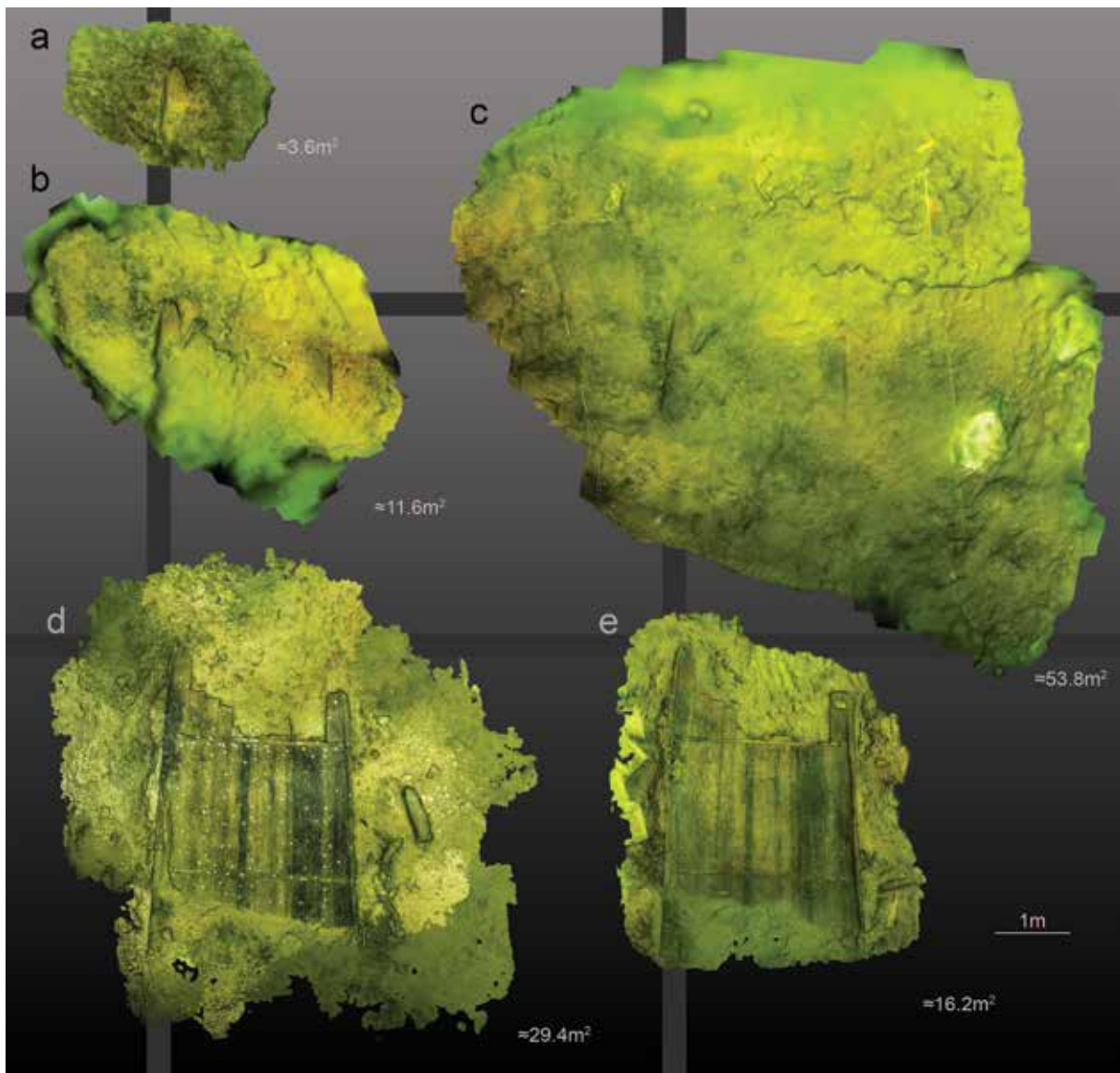
Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

269

Figure 4. Before final photogrammetric reconstructions a few sets of photographs were taken for testing of 3D modeling. Early at the beginning of excavation we took a set of 55 shots of the site (model a), 57 shots (model b) and approximately 450 shots (model c) to prove that the methods of photogrammetric 3D modeling will be successful at the end. After demonstrating that expected results will be achieved, the final two sets of photographs were taken on 13 October (314 shots; model d) and 15 October 2012 (502 shots; model e). (photo: R. Kovačič; 3D models: G. Berginc; processed with Mementify© PHOV).

significantly more sparse giving an insight of where additional photographs might be required. Figure 5b shows the triangulated mesh based on the point cloud from (a), and (c) shows how the texturing works. Since the set of photos focused on the middle part the texture is very detailed while becoming more granular when looking further from the centre.

Differences detected during comparative analysis between the 3D model and corresponding geodetic measurements indicate the weakness of using TLS measurements for documenting underwater sites. All TLS measurements were influenced by the direction of the river stream since the divers performing the measurement were influenced by it. Human error is unpredictable and above all, uncontrolled (Fig. 6).
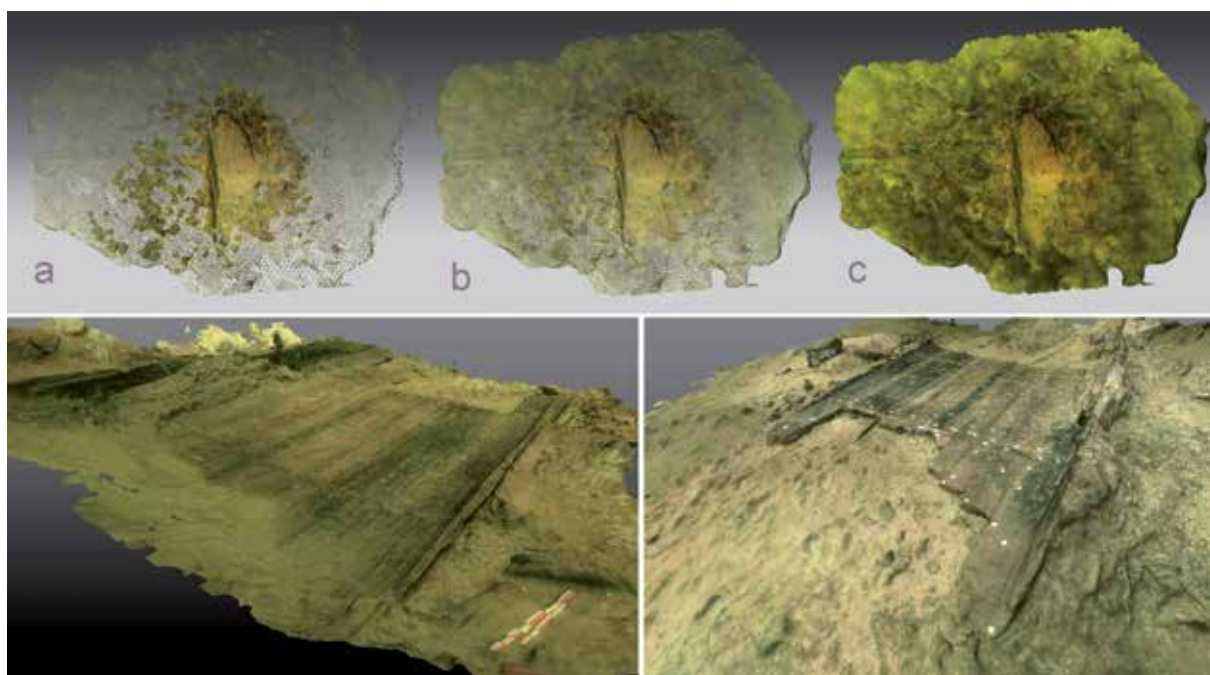
Miran Erič, Gregor Berginc, Rok Kovačič, Mitja Pugelj, Franc Solina

Figure 5. Testing the quality of 3D model (se Fig. 4, model a.) was done with MeshLab software. [*Top: a*] shows the number of points in cloud generated from set of 40 shots, [*Top: b*] shows the triangle mesh model and, finally [*Top: c*], we can see the surface reconstruction with texture. [*Bottom left*] Perspective view of 3D models: last model with 3.3M of faces and view from east towards west with field of view (FOV) of 53° degree. [*Bottom right*] model from 15 October 2012 with 3M of faces and the view from west towards east with FOV of 90° degree.
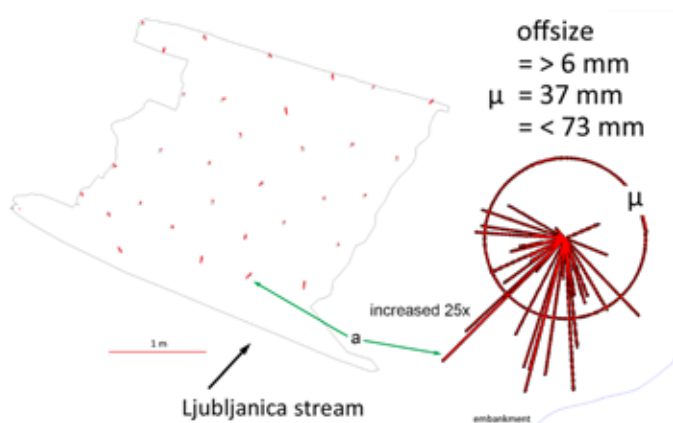

Figure 6. Differences detected during comparative analysis among the 3D model and the corresponding geodetic measurements indicate the delicacy of using TLS measurements for underwater site documenting. All TLS measurements were influenced by the direction of the river stream since the divers performing the measurement were influenced by it.

Results of comparative analysis of 3D models

Figure 7 a gives a visualization of the difference of two models. Visualization is done using methodology described in the subepigraph «Photogrammetric 3D modeling with MementifycPHOV Software». Red areas (or «hot spots») represent areas where the two models differ most (the colour is more intense, where the difference is bigger). Based on the visualization, we can make several observations. First, the error is larger on the edges (around the object) because of the changes in river bed (mud). Next, a stone (bottom left) is present in one model and not in the other. Regarding model quality, there are some visible differences on the edges of the model which could indicate errors in the integration or lack of images from certain angles. Furthermore, the difference on some long edges (left and right) and the slight difference on the flat

Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

271

surface in the middle of the model indicates that the integration process failed to exactly reproduce flat surfaces with scarce visual cues. This usually happens due to error accumulation and is a known problem in 3D model reconstruction. It is also possible that some of the difference at the edges is caused by misalignment of the model. However, we were not possible to confirm this.

Figure 7b and c represent the point density of the model taken on October 15 and October 19, respectively, and point density if we merge both points clouds (d).

As both models are fairly similar and have similar statistical properties, it is (in this case) hard to determine which model is better. Although model (b) has a better point density distribution, we can confirm is that there are no big defects in either of the two models. Lastly, it would be interesting to see if it would be possible to improve the quality of the model by integrating both models – the motivation for this is visible in figure 7 (d) as the point density is clearly better that on merged model in relation to each of the individual models. This task is left for future research.

Conclusion

Image based or photogrammetrically derived 3D models have proven to be very accurate, representative and usable for further analysis. For a manual documentation of the approx. 8 m² large surface of the barge, at least 25 hours of diving time would be required, while it took only 3 hours to take dedicated photographs in five different stages of investigation. Sets of photographs were used to reconstruct four different 3D models of the site. A comparison of two of them, made in the Computer Vision Laboratory, Faculty of Computer and Information Science, Univer-
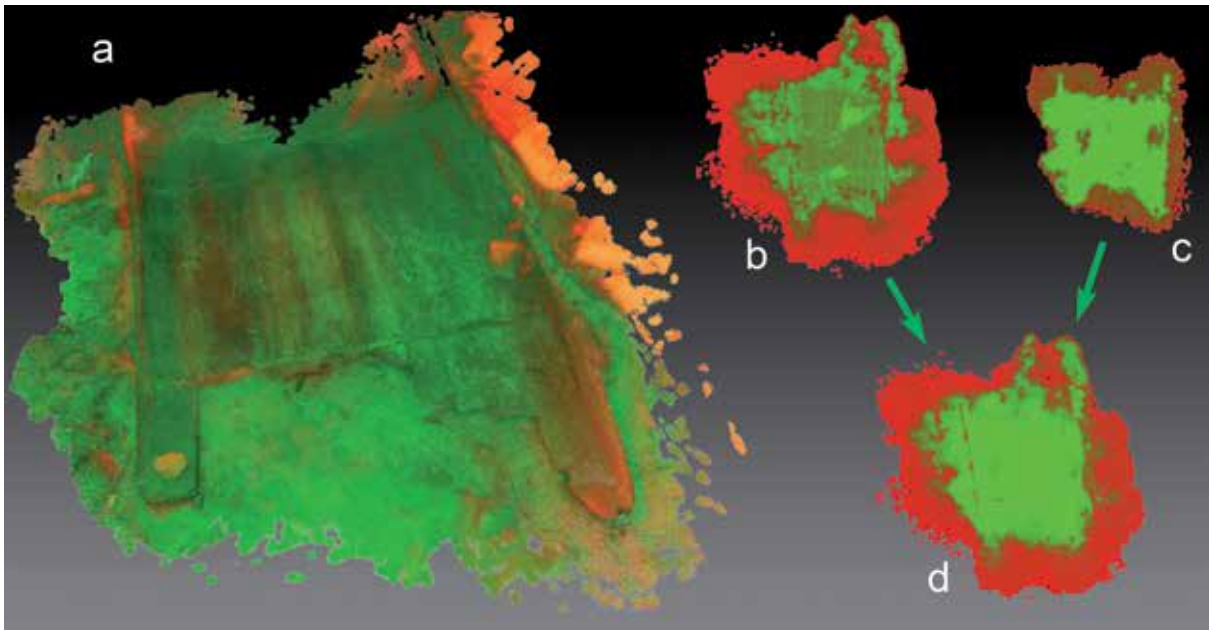

Figure 7. Comparison of two photogrammetric 3D reconstructions. Sets of photographs for the 3D model were taken on 15 and 19 October 2012. [*a*] – Complete correspondence of the morphology of both models (green); negligible deviations possibly related to the movement of the barge construction (orange hues). [*b*] Model taken at 15 October [*c*] Model taken on19 October [*d*] shows very good (green) correspondence of both models [*b* and *c*]. (Comparative analysis: M. Pugelj; photo: R. Kovačič; 3D model: G. Berginc; processed with Mementify© PHOV).

sity of Ljubljana, confirmed the accuracy of the documentation. The accuracy can be also confirmed indirectly, during the preparation of the graphic documentation from the obtained data. To verify the process of documentation, all measurements were also taken with a surveying instrument. The potential of the data acquired in this way is not limited to visualizing 3D models. In contrast to 2D photographs, where the viewpoint is fixed, and the already interpreted 2D plans, a 3D model enables a simulated observation for study purposes from any virtual viewpoint and of any recorded surfaces and objects (Erič *et alii*, 2013; Stopinšek *et alii*, 2013). The morphological properties of 3D point clouds, which are a complete recording of the present state, open up countless options for further analyses of the 3D model. This is especially important because the investigation of an archaeological site is usually physically limited to the duration of the fieldwork and is later, if preserved *in situ*, difficult to access or most often destroyed. 3D models allow us to systematically and in a planned way study, segment and classify selected surfaces. Using automatic analysis of 3D surfaces, we can search for specific features that could otherwise easily be overlooked *in situ*. Also important is the archival sustainability of digital archaeological documentation, which forms the basis for later study, interpretation and promotion.

Acknowledgment

References

Čufar, K.; Merela, M., and Erič, M. (2014): «A Roman barge in the Ljubljanica river (Slovenia): wood identification, dendrochronological dating and wood preservation research». In *Journal of Archaeological Science*, vol. 44, pp. 128-135.

De Reu, J. *et alii* (2014): «On introducing an image-based 3d reconstruction method in archaeological excavation practice». In *Journal of Archaeological Science*, vol. 41, pp. 251-262.

Drap, P. *et alii* (2013): «Underwater photogrammetry for archaeology and marine biology 40 years of experience in Marseille, France». In *Proceedings of the 2013 Digital Heritage International Congress 2013, 28 Oct - 1 Nov, Marseille, France, IEEE*. Edited by Addison, A. C. *et alii,* vol. 2, Piscataway, N. J., Institute of Electrical and Electronics Engineers, pp. 97-104.

Erič, M. (2009): *Rimska tovorna ladja SI-80: poročilo o nadzoru stanja ladje po posegih ob Sinjegoriških ribnikih*. Ljubljana, Zavod za varstvo kulturne dediščine Slovenije, Center za preventivno arheologijo. (Poročila oddelka za podvodno arheologijo vol. 1). Available at: https:// uni-aas.academia.edu/MiranEric/REPORTS [Accessed: January 6th 2015].

Erič, M. (2015): «Academia. Academic research paper platform». [Online] Available at: https://uni-aas. academia.edu/MiranErič. [Accessed: January 29th 2015].

Erič, M., and Gaspari, A. (2009): *Sinja Gorica: poročilo o arheološkem podvodnem pregledu struge reke Ljubljanice na območju zavarovanja desne brežine ob Sinjegoriških ribnikih*. Ljubljana, Zavod za varstvo kulturne dediščine Slovenije. (Poročila skupine za podvodno arheologijo, vol. 28). Available at: https://uni-aas.academia.edu/MiranErič/REPORTS. [Accessed: January 6th 2015].

273

Successful use of temporary underwater 3D documenting methodology: Early Roman barge from...

Erič, M. *et alii* (2013): «The Impact of the Latest 3D Technologies on the Documentation of Underwater Heritage Sites». In *Proceedings of the 2013 Digital Heritage International Congress 2013, 28 Oct - 1 Nov, Marseille, France* (Marseille, 2013). Edited by Addison, A. C.; Guidi, G.; De Luca, L., and Pescarin, S., Marseille, IEEE, n.º 2, pp. 281-288.

Erič, M. *et alii* (2014): «Zgodnjerimska ladja iz Ljubljanice pri Sinji Gorici = Early Roman barge from the Ljubljanica river at Sinja Gorica». In *Arheološki vestnik*, vol. 65, pp. 187-254.

Furukawa, Y., and Ponce, J. (2010): «Accurate, Dense, and Robust Multiview Stereopsis». In *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 8, pp. 1362-1376.

Gaspari, A. (2015): «Academia. Academic research paper platform». [Online] Available at: https://independent.academia.edu/AndrejGaspari. [Accessed: January 29th 2015].

Gaspari, A., and Erič, M. (2001): «Podmorske raziskave antičnega brodoloma Grebeni pri Silbi». In *Arheo*, vol. 21, pp. 97-99. [Online]. Available at: https://uni-aas.academia.edu/MiranErič/Papers. [Accessed: January 6th 2015].

Gaspari, A.; Erič, M., and Odar, B. (2011): «A Palaeolithic wooden point from Ljubljansko barje, Slovenia». In *Submerged prehistory*. Edited by Benjamin, J. *et alii,* Oxford, Oxbow Books, pp. 186-192.

Gaspari, A.; Erič, M., and Odar, B. (2012): «Paleolitska lesena konica iz Ljubljanice». In *Potopljena preteklost. Arheologija vodnih okolij in raziskovanje podvodne kulturne dediščine v Sloveniji. Zbornik ob 128-letnici Dežmanovih raziskav Ljubljanice na Vrhniki (1884-2012)*. Edited by Gaspari, A., and Erič, M., Radovljica, Didakta*,* pp. 231-238.

Gluščević, S. (2009): «The Roman shipwreck from the 1st century AD at Grebeni by the island of Silba (preliminary results)». In *Archaeologia Maritima Mediterranea,* vol. 6, pp. 69-87.

Holt, P. (2003): «An assessment of quality in underwater archaeological surveys using tape measurements». In *The International Journal of Nautical Archaeology*, vol. 32, n.º 2, pp. 246-251.

Jaklič, A.; Leonardis, A., and Solina, F. (2000): *Segmentation and recovery of superquadrics.* Kluwer.

Kazhdan, M.; Bolitho, M., and Hoppe, H. (2006): «Poisson Surface Reconstruction». In *SGP 2006. Symposium on geometry processing. Fourth Eurographics symposium on geometry processing, Cagliari, Sardinia, Italy, June 26-28, 2006*. Edited by Polthier, K., and Sheffer, A., Aire-la-Ville, Eurographics Association, pp. 61-70.

Lowe, D. G. (2004): «Distinctive Image Features from Scale-Invariant Keypoints». In *International Journal of Computer Vision*, vol. 60, n.º 2, pp. 91-110.

Mihajlović, I. (2013): «The Sutivan shipwreck – a cargo of sarcophagi and stone of the Roman period». *Skyllis*, vol. 21, pp. 57-62.

Snavely, N. *et alii* (2010): «Scene Reconstruction and Visualization From Community Photo Collections». In *Proceedings of the IEEE*, vol. 98, n.º 8, pp. 1370-1390. [Online]. Available at: http://dx.doi.org/10.1109/JPROC.2010.2049330. [Accessed: January 6th 2015].

Solina, F., and Bajcsy, R. (1990): «Recovery of parametric models from range images: The case for superquadrics with global deformations». In *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 12, n.º 2, pp. 131-147.

STOPINŠEK, Ž. *et alii* (2013): «Uvajanje 3D tehnologij pri varstvu kulturne dediščine». In *ROSUS 2013: računalniška obdelava slik in njena uporaba v Sloveniji 2013. Zbornik 8. strokovne konference, Maribor, 21. marec 2013*. Edited by POTOČNIK, B., Maribor, Fakulteta za elektrotehniko, računalništvo in informatiko, Inštitut za računalništvo, pp. 89-97. Available at: http://cobsis.uni-mb.si/rosus2013/ROSUS2013-splet.pdf. [Accessed: January 6th 2015].