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Underwater Photogrammetric Mapping of an Intact Standing Steel Wreck with ROV

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Abstract: This paper presents the results of an underwater photogrammetric survey of an intact standing steel wreck with high vertical profiles from the seabed at 60 meters depth. The survey was conducted in Trondheim Harbour in August 2014 using a Remotely Operated Vehicle (ROV) equipped with a stereo camera rig. The paper demonstrates how the emergence of commercially available photogrammetric software has reduced the required resources for creating high-resolution 3D-models of archaeological sites from photographs. At the same time, the resources and ROV-pilot skills required for the survey itself still represent an obstacle for the end users. The results and experiences of this survey are therefore used as the basis for a discussion on the possible benefits, challenges and strategies for conducting such a survey autonomously.

Keywords: Unmanned Underwater Vehicles (UUV), Marine archaeology, Mapping, UUV vision systems, Photogrammetry

1. INTRODUCTION

Only a fraction of our cultural heritage deposited on the seabed has been located and investigated, with UNESCO (2015) estimating over 3 million undiscovered shipwrecks spread across the planets oceans. Submerged prehistoric landscapes and shipwrecks deposited on the seabed are non-renewable sources to understanding and knowledge of our past, and the scientific community and antiquarian authorities around the world are working against the clock to secure as much of this heritage as possible for posterity. Climate change and increased commercial activities in the marine environments put this cultural heritage under pressure, and accentuates the need for new and efficient methods for recording and managing underwater cultural heritage.

Recent years have seen advances within underwater robotics that can remedy this situation by reducing the dependency on divers. Simultaneously, developments in sensor technologies and data processing have lead to relatively inexpensive commercially available off-the-shelf digital underwater cameras and photogrammetry software that can be run on a powerful but ordinary PC.

The inherent optical properties of the water (light reflectance, scattering and attenuation) means algorithms intended for underwater computer vision generally need to be more robust than algorithms intended for use in air. While the Scale Invariant Feature Transform (SIFT) is one of the most efficient feature detectors in many applications, Meline et al. (2012) demonstrated how suspended particles causes the performance of SIFT to deteriorate severely relative to other approaches. Similarly, Campos et al. (2014) demonstrated how surface reconstruction methods with insufficient levels of noise tolerance can give wildly varying results for underwater datasets.

McCarthy and Benjamin (2014) have shown how a diver-based photogrammetric approach can significantly improve the efficiency of the process of recording underwater cultural heritage. Taking the diver out of the equation by using a Remotely Operated Vehicle (ROV) as a platform for data capture removes two very limiting operational constraints (depth and bottom time). Removing the pilot as well by having an Autonomous Underwater Vehicle (AUV) perform this task autonomously would represent a significant breakthrough for marine archaeological recording. Some photogrammetric AUV surveys have been conducted, but are restricted to wrecks and seafloor that provide a relatively flat and benign environment for AUV robotic operations (Foley et al., 2009; Johnson-Roberson et al., 2010; Gracias et al., 2013; Demesticha et al., 2014).

Drap et al. (2013) demonstrated an ROV based photogrammetric survey of parts of a more threedimensional wreck, relying on a combination of high resolution images and sonar data to construct a georeferenced 3D-model. The reliance on sonar data increases the number of dives required to collect the necessary data.

In this paper we will present the process and results from an ROV based photogrammetric recording of a shipwreck

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with a high vertical profile. This recording demonstrates how accurate 3D-models can be produced relying only on lower resolution (1.4 megapixel) cameras and ROV navigation data for georeferencing, thus increasing the efficiency of a survey. The main contribution is in the analysis identifying the challenges and potential strategies for automating such a survey.

Section 2 presents the wreck and the motivation for its selection. Section 3 describes the method, hardware and software used for the data acquisition and processing. The experimental results are presented in section 4. The results and experiences from this recording is then analyzed in section 5, focusing on strategies for automating the process and exploring the potential benefits for marine archaeology and other marine sciences. Finally, a conclusion is given in section 6.

2. M/S HERKULES

The tugboat M/S Herkules sank just outside Trondheim Harbour on the 16th of September 1957 (Dykkepedia, 2015). While Herkules was towing the 9000 tonne M/S Lars Mehling, the cable ended up being pulled across the vessel. This caused the vessel to lean heavily towards port and rapidly take in water. No lives were lost.

Today the wreck rests on its keel at 60 meters depth with the top of the mast reaching 10 meters above the sea floor. The bow rises over the sea floor while the stern is buried in the sand, and the total length of the visible wreck is 20-25 meters.

2.1 Relevance of the wreck

This wreck was not chosen for any kind of archaeological significance. It is a well-known wreck frequently visited by technical divers. Rather, it was chosen for its close proximity to Trondheim, ease of access and limited size. Choosing such a new wreck in good structural condition also meant the risk of doing irreparable damage to an important archaeological find was essentially eliminated.

At the same time, this wreck demonstrates several of the challenges that will need to be resolved for a future autonomous survey approach.

The wreck has got a complex 3D-structure with both horizontal and vertical faces, and even some overhang for the lower part of the bow. Covering parts of the wreck are numerous ropes and wires, both part of the original construction and fishing equipment having caught on the wreck. This poses a risk for entangling the ROV and restricts how close the ROV is able to get to the steel parts of the wreck. The ropes and wires also pose a challenge for the modelling, being rather thin and complex compared to the solid steel plates.

Like any object with a high vertical profile on an otherwise flat seabed, manmade or natural, the wreck attracts biology like fish and crustaceans. For photogrammetry software assuming a stationary scene, these moving creatures can give false matches and erroneous camera positions. Generally, this means they need to be masked out of the images in the preprocessing, which can be time consuming.

3. METHOD

The survey of M/S Herkules was conducted on the 25th and 26th of August 2014.

3.1 Minerva ROV

Minerva is a SUB-fighter 7500 ROV made by Sperre AS in 2003 for NTNU. It is a medium sized ROV (144x82x81 cm, 485 kg), and is a frequently used test platform for navigation and control research. Usually deployed from the NTNU research vessel (RV) Gunnerus, it is powered from and communicates with the surface vessel through a 600 m umbilical. All systems needed for operation such as power supply, navigation computers and monitors are fitted inside a 15 foot container.

For this survey, the ROV was also equipped with a stereo camera rig. This features two Allied Vision GC1380C cameras mounted in parallell on a horizontal bar, 42cm apart at a 45° forward facing angle. The cameras have a resolution of 1360x1024 pixels and are capable of recording at 20 frames per second. Their high light sensitivity and signal to noise ratio makes them suitable for underwater operation. The reduced resolution, combined with keeping the recording at 0.5 fps to reduce the number of redundant images, keeps the amount of data at a manageable level for the postprocessing stage. The orientation of the camera rig was chosen both for ease of assembly and to be able to capture images of both vertical and horizontal faces with the same setting.

Operating at depths from 50 to 60 meters in the Trondheimsfjord means there is basically no ambient light. The lighting for operation was provided by two HMI lamps and two halogen lamps mounted on the horizontal top bar on the front of the ROV.

The ROV can be piloted manually using a joystick console, or automated using a Dynamic Positioning system (DP) developed and continuously expanded at NTNU. For more details on Minerva and the DP system, the reader is referred to Dukan et al. (2011) and Sørensen et al. (2012).

3.2 Image capture strategy

To minimize the risk of cable entanglement and account for the limited ROV-time available, the survey was split in two: The starboard side of the wreck was mapped the first day with Gunnerus stationed north (the wrecks starboard) of the wreck, and the port side was mapped the second day with Gunnerus stationed south of the wreck.

While Minerva has got automated altitude control, no automated feature based navigation system for keeping horizontal distance to an unmapped object is currently implemented. As a result, the survey was conducted using manual control and a simple rotating sonar providing distance to the wreck. An archaeologist also continuously evaluated the captured images during the survey, giving feedback on image quality. A distance of 2-3 meters to the wreck was deemed to yield the desired lighting and image quality, while not being to risky (with regard to entanglement) or difficult for the pilot to maintain.

The main survey pattern was chosen as a vertical lawnmower pattern with transects along constant depths (see figure 1). By choosing constant-depth transects, the automatic depth control could be used, reducing the complexity for the pilot. This also reduced the risk of current related drift producing random gaps between transect lines.

The depth difference between the transects was approximately 1 meter the first day. This was reduced to approximately 0.8 meters on the second day, based on initial overnight processing of the data indicating insufficient vertical overlap. In addition to these vertical lawnmower patterns, some additional images of the flatter top of the wreck were collected because the coverage of this area was deemed insufficient.

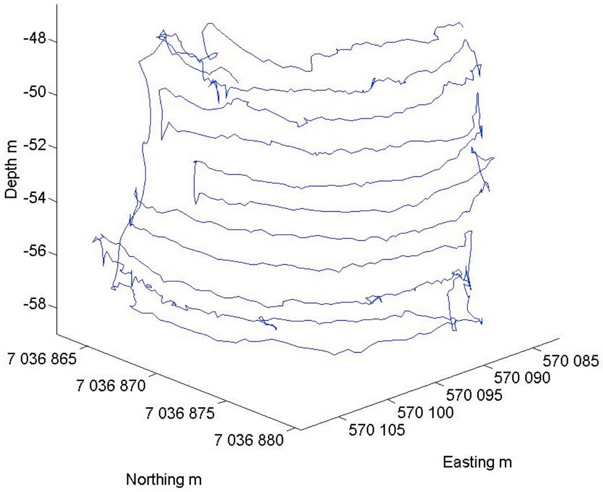

Fig. 1. ROV track for day 1 survey (starboard side of wreck)

3.3 Data processing

An overview of the processing pipeline is given in figure 2. Online data from the ROV is collected using LabVIEW (NI, 2015).

Due to the lack of automatic target distance control, quite a few images became underexposed while some became overexposed. In order to compensate for this, the images were colour corrected using the Automatic White Balance function in the open source image manipulation program GIMP 2.8 (GIMP, 2015). This command automatically adjusts the colours of the image by stretching the red green and blue channels separately. While this solution is not ideal, figure 3 demonstrates it offers a significant improvement. More importantly, the process is fast and can be run on the entire image set using the Batch Image Manipulation Plugin. With a dataset of several thousand images, efficient processing is obviously essential.

Agisoft Photoscan 1.1 (Agisoft LLC, 2015) is a commercially available program for producing photogrammetry models from regular 2D-images. While it does not specificly support underwater imagery, version 1.1 does have fisheye-camera support implemented. A fisheye lens in air displays some of the same warping behaviour as a regular lens in water, and thus improves the result when the software is applied to underwater images. The intrinsic parameters of the cameras were initially unknown and were estimated by the software as part of the aligning process. The aligning process produces a sparse point cloud (figure 5), and further processing yields a dense point cloud (figure 6) and a 3D-mesh (figure 7). Finally, a mosaic of the original images are projected onto the 3D mesh, creating the final model seen in figures 8-11.

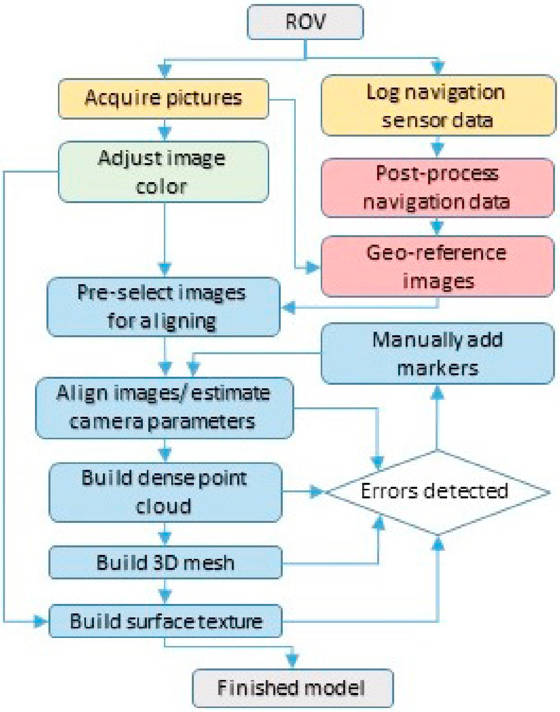

Fig. 2. Processing pipeline. Task color describes the software used: Yellow=LabVIEW (online), green=GIMP, red=MATLAB, blue=Agisoft Photoscan.

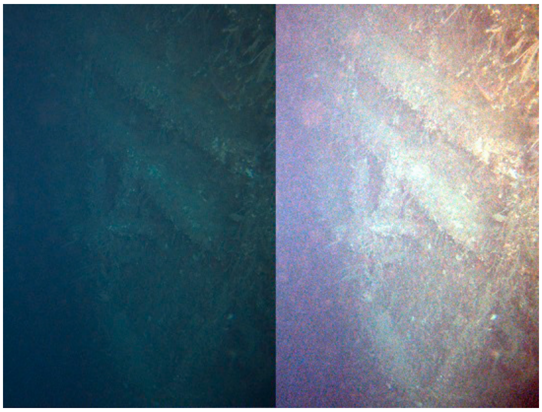

Fig. 3. Image from the bow of M/S Herkules, original on the left, colour adjusted on the right

Poor image quality and lack of discernable features can lead to images being improperly aligned, or not aligned at all. Large, obvious errors in camera orientation or position can be reset directly. More subtle errors can also give a large impact if they accumulate over sequential images, but may remain hidden until later in the processing. To counteract these, markers can be added manually to multiple images indicating a shared feature. The complete model is then realigned with the added information of the marker(s).

	East	North	Altitude	Total
Error (full set)	1.35m	1.40m	0.14m	1.95m
Error (wild point excl.)	0.80m	1.10m	0.14m	1.37m
	Yaw	Pitch	Roll	Total
Error	31.5°	3.9°	5.7°	32.2°

Table 1. Camera accuracies (RMS) estimated by Agisoft

Using the timestamps of the recorded images and the navigation data, the camera positions can be calculated using MATLAB (MathWorks, 2015). Agisoft does calculate its own camera positions, but the navigation data provides geolocalization and scaling of the model. The navigation data also speeds up the aligning process, since the software can skip comparing images that are too far from each other to cover the same scene.

4. RESULTS

Both survey days consisted of approximately 40 minutes of effective ROV-time on the wreck, resulting in a total of 4715 images.

Table 4 displays the root mean square (RMS) difference between the positions provided by the DP-system and the ones calculated by Agisoft. A jump in the absolute position measurement from Gunnerus caused 28 sequential images to receive an obvious error exceeding 10 meters, separate values excluding these images are therefore included. The quality of the navigation data was poor compared to similar cruises with the same system. The wreck may have reflected/blocked the acoustic position measurements. Furthermore, the steel wreck may have influenced the magnetic heading measurements, which in turn causes the error induced by the offset between cameras and acoustic transponder to become significant.

For the Herkules images, 4423 out of the original 4715 images were successfully aligned (figure 4) using 34 manually placed markers. The finished model is comprised of 1,450,000 vertices and 2,900,000 faces.

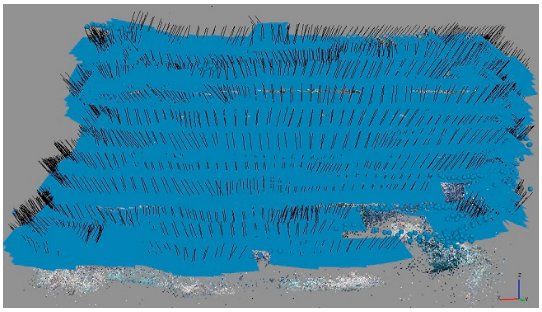

Fig. 4. Aligned cameras seen from starboard

The only quality measurement of the finished model presently available is the high level of concistency. Early results from a separate study on a nearby flat wreck using the same equipment indicates errors in length measurements below 1%, but with significantly better navigation accuracy. Assuming length accuracy is linearly dependant on navigation accuracy, errors in length measurements approaching 3% could be expected for the Herkules model.

A dive using technical scuba divers is planned to be conducted during spring/summer of 2015 to recover various length measurements to be compared to the digital model.

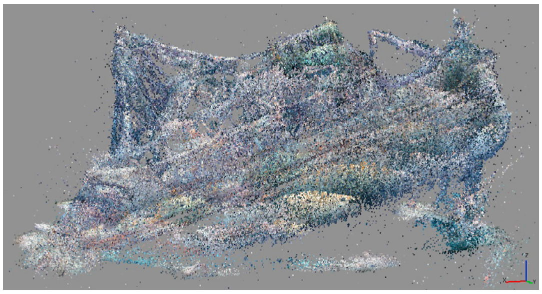

Fig. 5. Sparse point cloud model seen from starboard

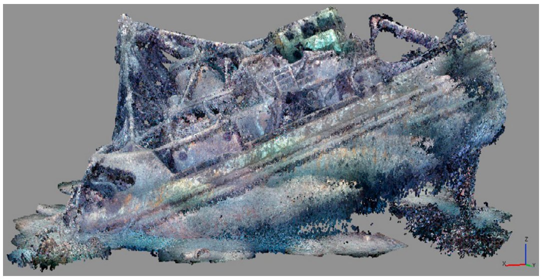

Fig. 6. Dense point cloud model seen from starboard

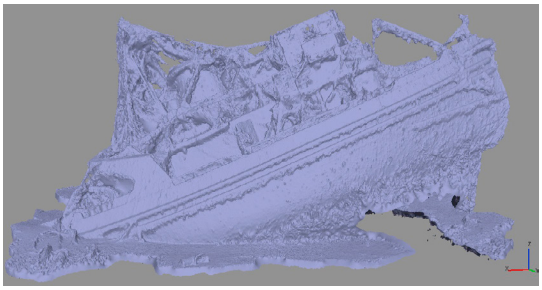

Fig. 7. Mesh model seen from starboard

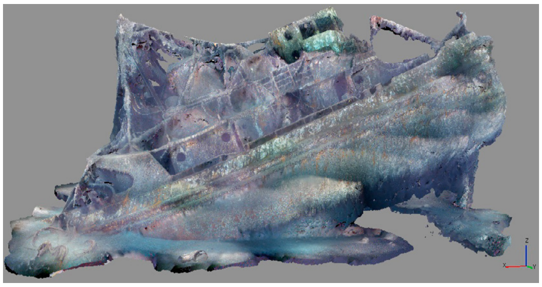

Fig. 8. Finished model seen from starboard

5. DISCUSSION

This section describes the experiences that can be drawn from the Herkules survey, identifying issues that need to be handled and suggesting potential improvements.

The quality of a finished 3D-model will always depend on the quality of the captured images, which in turn depends on the image capture strategy. When comparing the model sides based on images from day 1 (figure 8) and day 2 (figure 10), there is an obvious increase in quality: Figure 8 features highly visible boundary lines between the images captured at different depths, while layer transitions in figure 10 are smooth. This improvement can be attributed to three main causes: Reduced depth intervals leading to increased vertical overlap, increased attention to distance

Fig. 9. Finished model seen from the bow

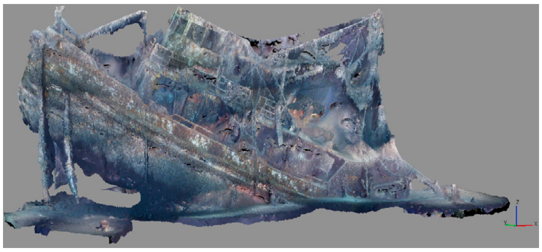

Fig. 10. Finished model seen from port

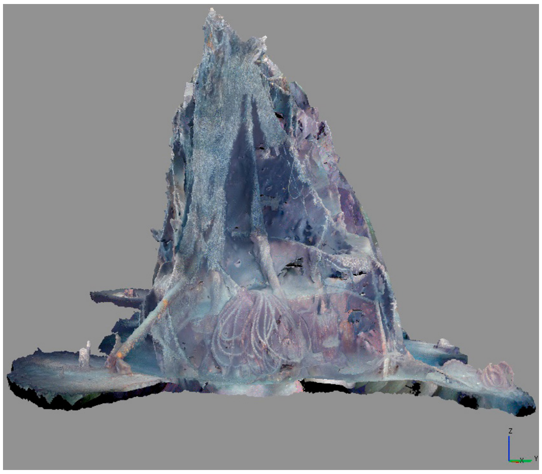

Fig. 11. Finished model seen from the stern

between ROV and wreck giving better image exposure, and a more beneficial positioning of RV Gunnerus leading to higher quality acoustic position measurements.

In our case, having the cameras mounted side by side while having horizontal runlines gave excessive horizontal overlap while vertical overlap at times was too low. To achieve better overlap, the camera rig should be mounted perpendicular to the runlines. Keeping the runlines horizontal and flipping the camera rig might be the simplest solution seen from a navigational standpoint, while opting to keep the rig horizontal and using vertical runlines may give better ROV stability.

The camera rig with fixed orientation and reduced resolution has been demonstrated to be able to capture a model giving a better overview of the wreck than regular video or scuba diving. This does come with some limitations when it comes to studying smaller objects which may have too low resolution or not enough coverage. Having a mobile high resolution camera, for instance mounted on a robotic arm would allow closer inspection of specific objects of interest, resulting in local high resolution models.

Because light is rapidly attenuated in water, both the distance between the cameras and the target and the distance between the light sources and the target has a high impact on the image quality. As demonstrated in figure 3, even simple post-processing of images can improve the quality, and more advanced post-processing techniques will likely offer further improvements. Any such techniques should be automatic, since the amount of images effectively excludes manual adjustment. However, the end result will always be limited by the raw data, so improving the raw footage through better distance and lighting control should be a high priority. By integrating the stereocameras with the control system, similar to Negahdaripour and Firoozfam (2006), a distance feedback of the overlapping field of vision would be achieved. A more complex single-camera-approach like the Direct camera Pose Registration Structure From Motion (DPR-SFM) of Nicosevici et al. (2009) could also be used, but since the system is already equipped with stereocameras, not utilizing the available stereovision would be counterintuitive.

For a sufficiently large ROV, one could also envision a distributed lighting rig system automatically adjusting an array of lights to ensure even scene exposure. Through the distance feedback of the stereocameras, the round-trip distance of the light (source-scene-camera) from each source could be estimated and the light intensity adjusted accordingly.

Being able to handle mobile biology such as fish, both as part of the online algorithm and during post-processing, will be important when mapping such 3D-structures. Structures rising high above an otherwise flat sea bed tends to attract a lot of biology, and if the creatures move between images, false matches are likely to be produced. Even slow moving biology like starfish might cause issues if the survey is carried out over a prolonged period of time. While Agisoft does contain functionality to mask out unwanted objects, this is very time consuming for a large image set, so some form of automation would be helpful.

The complete dataset, both raw and processed, will provide a useful testbed for implementations of the suggested improvements. The finished 3D-model could be used to generate outputs for cameras of simulated vehicles in any position or orientation. Adding the option of adjusting visibility and lighting conditions would allow assessment of the robustness of an experimental autonomous approach.

ROVs and AUVs can give marine scientists access to areas beyond the traditional limits for diving (e.g. deep or covered waters). With HD cameras and appropriate lights the field of view is not reduced, so visually there should be no cession of perceptive qualities. Comprehensive interpretation and understanding of features or objects on the seabed with dimensions that far exceeds the field of view can be difficult, and an accurate overview of e.g. a complex wreck site with pronounced 3D-structures is not easy to obtain. ROV-based photogrammetric recording can help marine scientists to overcome such difficulties.

For management of underwater cultural heritage this method will be particularly useful, since the number of relatively large steel wrecks older than one hundred years (UNESCO definition of UCH) will increase significantly in the coming years with all the wrecks from WWI. While many of these ships may have maintained a high degree of structural integrity, disintegration is only a question of time. A precise 3D model combined with full coverage photos will be very useful for interpreting and understanding such wreck sites, and also for determining their state of preservation. It will moreover enable archaeologists to do repeated, precise measurements of the exact same locations when revisiting the site, thus provide relevant data for monitoring purposes or for supporting management strategies and decisions. High resolution photo-rendered 3D-models are of course also very well suited for public dissemination and outreach (Chapman et al., 2006).

6. CONCLUSION

We have presented the results of an ROV-based photogrammetric survey of an intact standing steel wreck with a complex structure and high vertical profiles. The resulting 3D-model was reconstructed using available freeware and commercial software. The results highlight the potential improvements that can be achieved by reducing the reliance on a pilot, both in terms of data quality, but also in reducing the required resources for a survey even further. Further research into increasing the level of autonomy for such a survey is needed, and this dataset will become a useful testbed for new algorithms.

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REFERENCES

Agisoft LLC (2015). `http://www.agisoft.com`. Retrieved 9. March.

Campos, R., Garcia, R., Alliez, P., and Yvinec, M. (2014). A surface reconstruction method for in-detail underwater 3D optical mapping. *The International Journal of Robotics Research*.

Chapman, P., Conte, G., Drap, P., Gambogi, P., Gauch, F., Hanke, K., Long, L., Loureiro, V., Papini, O., Pascoal, A., Richards, J., and Roussel, D. (2006). VENUS, Virtual ExploratioN of Underwater Sites. In *The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, VAST*.

Demesticha, S., Skarlatos, D., and Neophytou, A. (2014). The 4th-century B.C. shipwreck at Mazotos, Cyprus: New techniques and methodologies in the 3D mapping of shipwreck excavations. *Journal of Field Archaeology*, 39, 134–150.

Drap, P., Merad, D., Mahiddine, A., Seinturier, J., Peloso, D., Boï, J.M., Chemisky, B., and Long, L. (2013). Underwater Photogrammetry for Archaeology. What Will Be the Next Step? *International Journal of Heritage in the Digital Era*, 2, 375–394.

Dukan, F., Ludvigsen, M., and Sørensen, A.J. (2011). Dynamic positioning system for a small size ROV with experimental results. In *OCEANS 2011 IEEE - Spain*.

Dykkepedia (2015). `http://www.dykkepedia.com/wiki/Herkules`. Retrieved 9. March.

Foley, B.P., Dellaporta, K., Sakellariou, D., Bingham, B.S., Camilli, R., Eustice, R.M., Evagelistis, D., Ferrini, V.L., Katsaros, K., Kourkoumelis, D., Mallios, A., Micha, P., Mindell, D.A., Roman, C., Singh, H., Switzer, D.S., and Theodoulou, T. (2009). The 2005 Chios Ancient Shipwreck Survey: New Methods for Underwater Archaeology. *Hesperia: The Journal of the American School of Classical Studies at Athens*, 78(2), 269–305.

GIMP (2015). `http://www.gimp.org/`. Retrieved 9. March.

Gracias, N., Ridao, P., Garcia, R., Escartin, J., L'Hour, M., Cibecchini, F., Campos, R., Carreras, M., Ribas, D., Palomeras, N., Magi, L., Palomer, A., Nicosevici, T., Prados, R., Hegedus, R., Neumann, L., de Filippo, F., and Mallios, A. (2013). Mapping the Moon: Using a lightweight AUV to survey the site of the 17th century ship 'La Lune'. In *OCEANS - Bergen, 2013 MTS/IEEE*, 1–8.

Johnson-Roberson, M., Pizarro, O., Williams, S.B., and Mahon, I. (2010). Generation and visualization of large-scale three-dimensional reconstructions from underwater robotic surveys. *Journal of Field Robotics*, 27(1), 21–51.

MathWorks (2015). `http://se.mathworks.com/products/matlab/`. Retrieved 9. March.

McCarthy, J. and Benjamin, J. (2014). Multi-image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach. *Journal of Maritime Archaeology*, 9(1), 95–114.

Meline, A., Triboulet, J., and Jouvencel, B. (2012). Comparative study of two 3D reconstruction methods for underwater archaeology. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, 740–745.

Negahdaripour, S. and Firoozfam, P. (2006). An ROV Stereovision System for Ship-Hull Inspection. *Oceanic Engineering, IEEE Journal of*, 31(3), 551–564.

NI (2015). `http://www.ni.com/labview/`. Retrieved 9. March.

Nicosevici, T., Gracias, N., Negahdaripour, S., and Garcia, R. (2009). Efficient Three-dimensional Scene Modeling and Mosaicing. *J. Field Robot.*, 26(10), 759–788.

Sørensen, A.J., Dukan, F., Ludvigsen, M., Fernandez, D.A., and Candeloro, M. (2012). *Further Advances in Unmanned Marine Vehicles*, chapter 6: Development of Dynamic Positioning and Tracking System for the ROV Minerva, 113–128. IET, UK.

UNESCO (2015). The UNESCO convention on the protection of the underwater cultural heritage. `http://www.unesco.org/new/fileadmin/MULTIMEDIA/HQ/CLT/UNDERWATER/pdf/Info_kit/GB-2001CONVENTION-INFOKIT%2007-2009.pdf`, Retrieved 9. March.