AN ‘OPEN’ METHOD FOR 3D MODELLING AND MAPPING IN UNDERWATER ARCHAEOLOGICAL SITES

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KEY WORDS: Underwater, archaeology, computer vision, photogrammetry, 3D reconstruction, open software

ABSTRACT:

Underwater photogrammetry is a difficult task by definition. When time limits are imposed on both acquisition and processing time, it becomes even more complicated. In addition when resources are limited and the main deliverable should be a complete 3D model, only a novel method may match the requirements. Under the aforementioned conditions, a new method using a combination of photogrammetry and computer vision techniques was utilised using open source software to face demands.

1. INTRODUCTION

Ancient shipwrecks provide the most direct and primary class evidence of seaborne trade and seafaring in the Mediterranean during antiquity. Their location, though, in an unfriendly environment for humans, makes their excavation very demanding in human resources and equipment. Therefore, it is essential to make the investigations cost- and effort- effective by using the best of the available tools, technical and technological. As good documentation is a particularly crucial process for the post-excavation archaeological study and assessment of a shipwreck site, the use of elaborate mapping techniques is indispensable during the excavation.

Photogrammetry is a well adopted method for underwater mapping, but not a trivial task at all (Canciani et al., 2002; Ludvigsen et al., 2006; Drap et al., 2007; Chapman et al., 2010). By definition ”Photogrammetry is the art, science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena” (Mc Glone, 2004). It is quite clear, that photogrammetry it is not a real-time or automated process. In fact most photogrammetric tasks are laborious and tedious. The much younger field of machine vision, takes advantage from computer vision algorithms and focuses on real time image exploitation for controlling a specific process or activity. Since photogrammetry’s entrance in the “digital era” it was a matter of time before embracing computer vision algorithms towards complete post-processing mapping automation.

1.1 Context of the research

Since 2007, a 4th century BC shipwreck has been investigated in Mazotos area, Cyprus (Demesticha, 2010). The site lies on a flat sandy sea bottom, in deep water (-45 m), with limited working time for divers. It is the first underwater archaeological project that has ever been undertaken by Cypriot institutions, so the resources are limited. Still, the significance of the site and the dense concentration of the finds in an almost undisturbed assemblage, increased the needs for careful digging and high precision monitoring of the daily excavation. Thus, given this specific nature of the shipwreck, decision was made from the beginning of the project that a 3-D reconstruction of the site should be the ultimate objective of the mapping process.

As in every archaeological excavation, artefacts cannot be removed if not mapped precisely. In this case, photogrammetry was used as the main mapping technique, so the team of surveyors were fully involved in the archaeological research: the development of the excavation depended on how quickly they accomplish their project, i.e. the digital recording of every find’s location. In other words, it became obvious that any delay caused during photogrammetric processing of the data would cause delay on the excavation and would have serious effects on its budget and planning. On the other hand, as in any close range project, the surveyor could be sure of the data collection consistency, only after they had successfully resolved bundle adjustment Therefore, the development of an automated process for bundle adjustment was necessary. Further more, the software used should be able to produce a complete 3D (not 2.5D) model of the trench area, by extracting a dense point cloud.

On the authors’ best knowledge, there is no commercial software fulfilling such demands. Photomodeler scanner doesn’t support automatic bundle adjustment and standard aerial photogrammetric softwares are expensive and do not support full 3D point cloud collection. Zscan scuba from Mensi, might have been an option but only for an excavation with considerable budget.

In underwater investigation, diving logistics raise a few more considerations. The Mazotos wreck lies in deep water and divers are only allowed 20 minutes bottom time before they start their decompression sequence. Considering the limited numbers of available divers in this project, one dive per day was to be devoted in photogrammetric documentation. In addition, camera calibration and photography over the whole area of interest should be done within the 20 minutes’ bottom time allowed per dive, camera calibration and photography over the whole area of interest should be done. Underwater currents made still photography or exact positioning and framing

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extremely difficult, and therefore the layout of the photography should be simple, fast and straight forward.

In sum, the main key factors of the particular case study were:

- Need for accuracy, completeness and reliability of the final product
- Limited budget for software and hardware, hardly covering a DSLR with housing
- Fast processing, so that a 3D model of the trench could be produced within an afternoon
- Limited time for photography (an average of 20 min per day)
- Need of a photographic process easy to adopt by non-experts, as photography was undertaken by divers with no experience in photogrammetry

To our best knowledge, previous known attempts for underwater digital mapping, had not met all the abovementioned needs without problems. In most similar cases, Photomodeler scanner software was adopted (Green et al., 2002; Canciani et al., 2002) and was also used in previous excavation periods at Mazotos (Demesticha, 2010; Skarlatos et al., 2010), but could not fulfil the requirements of speed, automation, good 3D modelling and non experts involvement, as it is after all a complete photogrammetric software. Although many options are preset for the inexperienced users, in the demanding underwater case a lot of parameterization should be done. Machine vision has been used in underwater mapping (Mahon et al., 2011), but requires significant post-processing time and additional equipment, while software is not commercially available. In addition the proposed methodology has been applied for mapping a site but not for monitoring a dynamically changing excavation process. Therefore, similar underwater task has never been undertaken so far.

During the 2010 field season at Mazotos, open source software fulfilling most of these requirements was experimentally used, but not fully explored. During the 2011 field season it was customised, implemented and extensively used as described below.

2. OPEN TOOLS AND METHODOLOGY

The main outline for any close range photogrammetric task towards a 3D model can be described as follows: layout of control points, measuring control points, camera calibration, photography, bundle adjustment, stereo matching and checking. Therefore appropriate open software tools should cover every step, but this not always the case. Remedies, customization and some adjustments in typical methodology were applied towards the final product.

Main open tools used in this approach are Bundler (Snavely et al., 2006) for bundle adjustment and CMVS along with PMVS (Furukawa et al., 2008; Furukawa et al., 2010) for dense point cloud extraction. Additionally, Meshlab (2011) was used to view and edit colour point clouds, Imagemagick (2011) and GIMP (2011) for photo editing, necessary in such environment with bad illumination conditions and heavy wavelength absorption.

2.1 Bundler

Orientation software is probably the most expensive and dedicated software in the aforementioned workflow. In general terms, input in such processes are the photos themselves, the camera calibration and initial values for the camera position and orientation. Most modern commercial implementations support self camera calibration but not all of them can handle unordered photographs with large bases and strong rotations. The core of this process consists from an interest point operator to locate distinctive points/features as tie points (Forstner et al., 1987; Harris et al., 1988), a point transfer algorithm (Tsingas, 1992) and least squares bundle adjustment (BA) supported with robust blunder detection.

Recent point extraction algorithms such as SIFT (Lowe, 1999), and SURF (Bay et al., 2008), not only do find more points than the aforementioned “photogrammetric” interest point operators (Lingua et al., 2009), but they also produce a useful set of descriptors for each point. These descriptors are being used to match features across images and successfully overcome point transfer problems and limitations; main reasons for constraining us in good layout photographs with uniform scale.

Modern point descriptors proved to be more appropriate for photogrammetric tasks such as automatic tie point extraction and digital surface model (DSM) creation (Lingua et al., 2009) at the cost of computation time. In addition SIFT implementations require a large amount of memory, which makes processing of standard aerial imagery problematic.

Bundler was created as a structure-from-motion (SfM) system for unordered image collections. It utilises SIFT for point extraction and uses as underlying optimization engine a modification of Sparse Bundle Adjustment (SBA) package from Lourakis and Argyros (2009). Input consists of a set of unordered photos with EXIF headers, a list of initial image matches as input. After processing it exports cameras’ intrinsic and extrinsic parameters. A computer literate user with no photogrammetric skills can produce impressive results with Bundler, orienting any number and kind of images with different focal length, large scale differences and rotations, with huge base lines.

Since Bundler was designed as SfM, it suffers in terms of georeferencing, use of a pre calibrated camera for all (or some) images and lack of metrics for the quality of the solution.

2.2 Patch-based Multi View Software

Although well accepted that multi image matching can provide more accurate and less noisy results than simple stereo, it hasn’t been adopted in commercial photogrammetric software yet (Skarlatos, 2006). In standard aerial photogrammetric tasks, Digital Elevation Model (DTM) acquisition is the most time consuming and error prone process, which would have benefited a lot of the use of multi image matching techniques.

PMVS (Furukawa et al, 2008) is open source multi-view stereo (MVS) software, that takes a set of undistorted images and corresponding focal lengths, to reconstruct 3D structure of an object or a scene visible in the images. Output is a set of oriented points, where both the 3D coordinate and the surface normal are estimated. The software handles options for template size, pyramid layers, minimum images per point, density and threshold, allowing full control over the output. The advantages of the software include automatic removal of moving objects, improved point accuracy due to multi-image utilization, avoidance of undesirable effects of multiple layers of points in overlapping areas, improved occlusion handling, uniform colour retrieval and normal calculation to points.

Furukawa et al. (2010) presented a method called Clustering Multi View Stereo (CMVS), to decompose large data sets into a set of manageable image clusters. The only input necessary is the maximum cluster size, which depends on the available memory. A Multi View Stereo (MVS) software can be used afterwards to process each cluster independently and in parallel, while the union of all the reconstructions would not miss any details that can be otherwise obtained from the whole image set. A typical pipeline is to run Bundler to get camera intrinsic and extrinsic parameters, use the provided Bundle2PMVS program to undistort imagery and then run CMVS and PMVS. Although all these programs are command line executables, there are implementations which provide a Graphic User Interface (GUI) to assist users to go through the workflow (2011). In this study, software used, was downloaded from http://www.visual-experiments.com/demos/sfmtoolkit/ (2011).

2.3 Georeferencing

Requirement for real measurements on the daily generated point clouds of the trench, in conjunction with the fundamental objective of the Mazotos project i.e. full 3D reconstruction of the shipwreck reveals PMVS's main drawback. SfM software is not designed for photogrammetric tasks and therefore point clouds created by PMVS have arbitrary scale, orientation and position in 3D space. Thus post processing for their registration in a global coordinate system is needed. Recovering the relationship between two different coordinate systems, given sets of corresponded points, is widely known as the absolute orientation problem and can be defined as a 3D similarity transformation with 7 unknown parameters:

$$x_2 = sRx_1 + t \tag{1}$$

where s = scale factor
R = rotation matrix
t = translation

Several methods addressing the aforementioned problem, have been developed and can be grouped in two categories, closed-form and iterative solutions. As mentioned in Eggert et al. (1997), closed-formed solutions outperform iterative methods because the latter depend on good starting estimates in order to achieve convergence. In our approach, initial use a closed-form algorithm is followed by least squares iterative optimization, hence taking advantage of both methods. In more detail, initial value for the scale factor is obtained as follows (Horn, 1986):

$$s = \sqrt{\sum_{i=1}^{n}\left\|x_{2,i}^{c}\right\|^{2} \Big/ \sum_{i=1}^{n}\left\|x_{1,i}^{c}\right\|^{2}} \tag{2}$$

where $x_{1,i}^{c}$, $x_{2,i}^{c}$ = points coordinates referring to the centroids
n = number of points

Subsequently, initialization for the remaining parameters, is obtained via Singular Value Decomposition (SVD) method, which was developed by Arun et al. (1987). According to this approach, after sifting all points coordinates to the centroid, the rotation R is computed via the SVD of a matrix **H** given by:

$$H = \sum_{i=1}^{n}\left(x_{2,i}^{c} \cdot x_{1,i}^{c\,T}\right) \tag{3}$$

Finally, initial values for the elements of the translation vector ***t*** are calculated from equation 1. After the initialization step, the optimal transformation is acquired by a least squares optimization implementation i.e. minimizing the sum of squares of Euclidean distances between the conjugated points. The process iterates until the elements of the shift vector $\delta\hat{x}$, fall below a certain limit. In practice values of 0.001 m and 0.0001 grad were used as thresholds, for translation parameters and angles respectively.

3. IMPLEMENTATION

3.1 Underwater photography

The underwater environment poses constraints with regard to the trivial over water photogrammetric photo shooting. It is necessary to clearly state the facts that govern underwater photography, before one can elaborate a photographic methodology towards the desirable result:

- The diver cannot stay still, because of currents and breathing, which causes slow but continuous ascend or descent moves.
- It is impossible to perfectly frame the area of interest if the camera hasn't live-view features. In addition mask, housing and surrounding conditions constrain flexibility or time for the photographer to clearly frame and shoot.
- Starting from the red and moving towards the blue wavelengths, sea water absorbs colors. Therefore, without use of flash color information disappears in depths bigger than 30m.
- Flash range is limited to 1.5m and there is strong color degradation after that range. Flash angles must be set with respect to the camera-object distance, otherwise backscattering will be too strong and destroy images.
- Illumination conditions are poor, and therefore aperture and speed must be carefully set, if flash is not available.
- The silt in the bottom can easily be disturbed and destroy visibility.
- Time limitation was set at 20 minutes.

Keeping in mind that Bundler and PMVS can automatically handle large sets of uncalibrated photographs, with large overlaps and strong rotations, employing true multi image stereo matching, makes it is easy to cope with most of the aforementioned restricting factors.

Figure 1: Example of raw imagery with use of flash. Note the strong color vignetting effect towards the edges of the photograph, in combination with the use of wide lens (photo A.Neofytou, © ARU, UCy, 2011).

By eliminating the need to shoot a calibration board, with different view angles prior to each photography, time is amble for photographing the whole trench in a single dive. Trying to imitate standard aerial photography layout, the diver may swim at certain height/depth above the trench (3m was the practice at Mazotos), in straight line with constant speed, taking photographs at a steady rate to ensure 70-80% along trip overlap. At the end of the line, the photographer should turn around and cover another strip with 50% overlap with the previous one. Taking more images that the absolutely minimum is not a problem when using automated techniques and therefore deviations from that pattern can be accommodated, provided there is amble coverage. As a general rule; diver can take photographs faster without worrying about the added labor during processing. This is not the case with manual orientation techniques, during which each image adds considerable labor.

After covering the trench with vertical imagery, diver may swim around the trench taking dense 45 degrees oblique photographs from approximately the same distance as the vertical ones.

Figure 2: Example of oblique photograph taken without flash. Note the complete lack of red color (photo L. Diamanti, © ARU, UCy, 2011).

Figure 3: Example of oblique photograph with use of flash. Color differences between foreground and background may lead to failure when matching SIFT descriptors among neighboring photographs (photo A.Neofytou, © ARU, UCy, 2011).

The quality of the photographs proved to be more of a problem than the photography itself. The use of flash combined with wide lens caused strong color vignetting effect (Mahon et al., 2011), which in return caused failure during SIFT point transfer (matching) within Bundler. In order to overcome his problem, it was decided to deactivate flashes. Although SIFT did find and successfully matched more points across images, there was significant loss of color information, which produced aesthetically poor, yet geometrically correct results.

During the project, two cameras were available, a Canon 550D with a 10-22mm zoom lens and a Nikon D200 with a 20mm lens. Both cameras were used during the field season, but the fixed lens solution prevailed. Camera was set to 1/60 speed priority to compensate diver continuous motion. Depth of field effect is quite low in short lenses, hence automatic alterations of aperture do not affect the object's sharpness, or camera geometry. During the photography the auto focus function was disabled in order to maintain constant focal length in all photographs.

The trench area covered an area of approximately 4m x 4m but not well defined from the beginning of the season. Therefore, each time a much wider area needed to be covered, in order to get enough information from the surroundings as well. Eventually, a roughly 5m x 5m area was covered and processed each time a new survey project had to be conducted. Photographs were being taken from a distance of 3m, covering an excavated area of 3m x 2m.

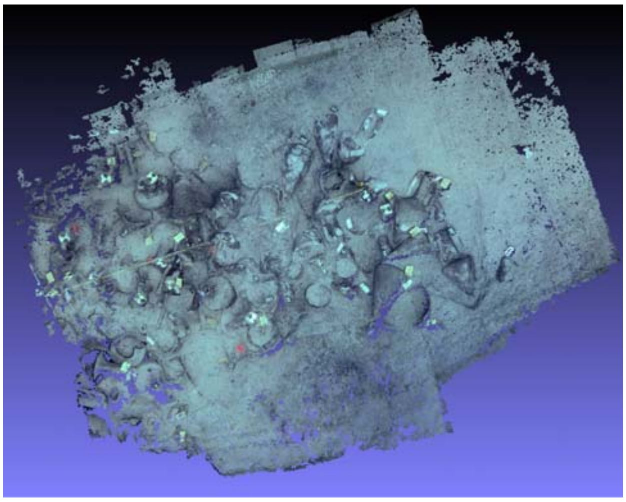

Figure 4: Point cloud with 1M points, created by 61 digitally color enhanced vertical photographs, shoot without flash (© D. Skarlatos, CUT & ARU, UCy, 2011).

3.2 From photos to point clouds

As an average, 60-70 photographs were taken daily over the 4x4m trench. The computer available was a Core Duo with 4GB of RAM running Windows XP64. The images were subsampled by 2, in order to accelerate the process, while loss of accuracy and detail was negligible. SIFT point extraction was the most important and time consuming part of the adjustment phase, with Bundler running in near real time. If SIFT algorithm doesn't recover enough points the process fails in two possible ways; either by adjusting only a portion of the images or calculating wrong intrinsic camera parameters. In such cases, changing SIFT parameters is necessary in order to force the algorithm to export more points. Since the camera's focal length was stable and approximately known by frequent underwater calibrations, initial focal length value was provided in Bundler. Usually, the whole process lasts less than 1.5 hours, including CMVS-PMVS data preparation.

Problems regarding the BA process were mainly caused due to erroneous camera focal length recognition by the software, poor coverage, inconsistent lighting conditions, and large angle for oblique photography. After resolving these problems by fine-tuning the photographic methodology, and familiarization with the software, the whole process became trivial.

Usage of CMVS and PMVS software is simple. User may keep default values, the most important being the minimum number of images that a point has to be matched. This parameter is set to 3, but 2 can be used in case there are areas without sufficient coverage. The process was time consuming, approximately 3-4 hours, running on the second pyramid (on already subsampled imagery) and matching every 2 pixels. Nevertheless the results are dense point clouds. On average, 1M points were being calculated for the wider area of the trench (5m x 5m), equivalent to 4 points per square cm.

The final point clouds demonstrate very good signal to noise ration due to software's ability to use multi image matching, hence minimizing noise. Performance of the whole process is impressive. It is noticeable that even photos with featureless sandy bottom, were correctly oriented and modeled with thousands of points (figures 4, 5, 6).

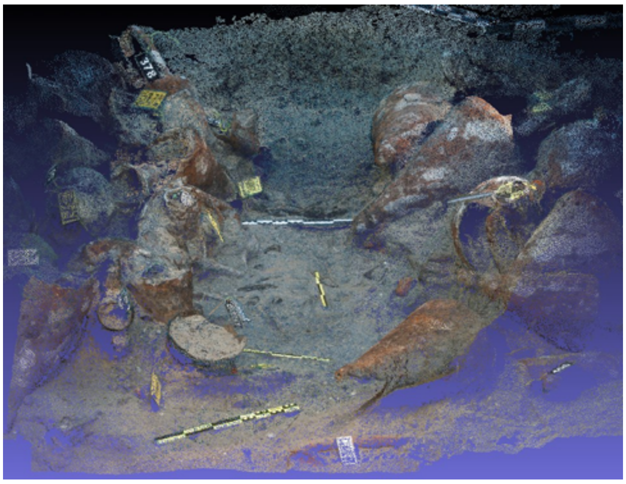

Figure 5: Point cloud with 1.1M points, created by 49 close oblique photographs shoot with flash, for detailed 3D modeling (© D. Skarlatos, CUT & ARU, UCy, 2011).

3.3 Georeferencing

The lack of stable control points surrounding the area of interest cased many problems. Due to sandy bottom, both a blemish and bliss, fixation of suitable long lasting control points without risking damaging the site is impossible. Therefore, plastic disks were positioned on half-buried (so difficult to move) and almost upright amphoras in order to be used as control points. These plastic disks, due to their placement and subsequent re-placement, suffer of positional inaccuracies of up to 0.03m. The accuracy in the position of these control points (targets) in the local coordinates, has been estimated in σX= 0.034 m, σY= 0.064 m, σZ= 0.052 m (Skarlatos et. al., 2010), according to Photomodeler block adjustment results.

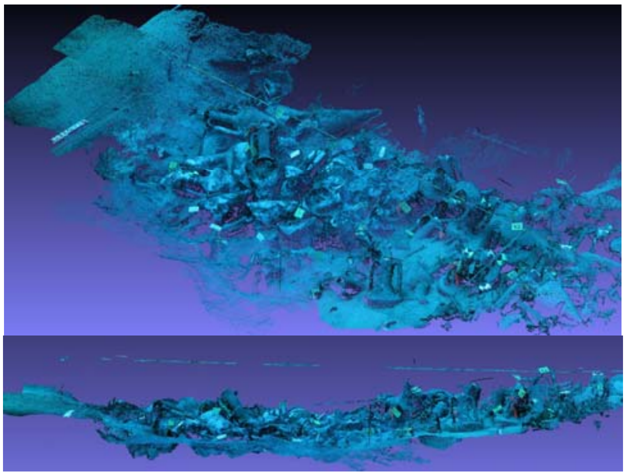

Figure 6: Different aspects of the same point cloud with 2.5M points, created by 150 oblique and vertical photographs shoot without flash, processed for digital contrast stretching. Note the thin lines of points on top of the point cloud, representing the guidance rope (© D. Skarlatos, CUT & ARU, UCy, 2011).

Moreover, these plastic disks can hardly support good geometry, as they mainly lie within the area of interest. As a minimum photogrammetric requirement, control points should be equally distributed over the edges of the area of interest. In this case control points were uneven and only covered the central part of the trench, causing rapid deterioration of accuracy in areas outside the control points' limits (figure 8).

3D point cloud registration, according to the aforementioned steps, was implemented in Matlab. Control points, were in most cases clearly distinguishable in the colored point clouds. The selection of the targets and the coordinate readout was manually carried out in Meshlab. It should be noted that the described registration method did not apply any robust technique (such as RANSAC) for outlier detection and elimination. Therefore the reliability of the selected points is crucial. The point selection step may not always be an easy task, regarding distribution's demands and visibility issues.

Nevertheless, since internal geometry of the point cloud is probably better that the control point coordinates, the least squares should minimize the total error by positioning the rigid point clouds "in between" the control points.

Date	1/6/11	9/6/11	17/6/11	21/6/11
# of control points	7	7	7	7
# of iterations	3	3	4	4
σ_0 (m)	0.017	0.010	0.013	0.014
max v_x (m)	0.019	0.023	0.015	0.017
max v_Y (m)	0.013	0.014	0.005	0.012
max v_Z (m)	0.037	0.021	0.033	0.018

Table 7: Indicative registration results. Residuals refer to control points only.

Table 7, demonstrates that the registration method has fast convergence, based on relatively small point sets. In terms of accuracy, the results are generally satisfactory considering the aforementioned control points' precision. Moreover, excavation's daily progress and finds' removal compels the use of different control points from one day to another. It is expected that if control point accuracy was better the registration accuracy would have been improved as well.

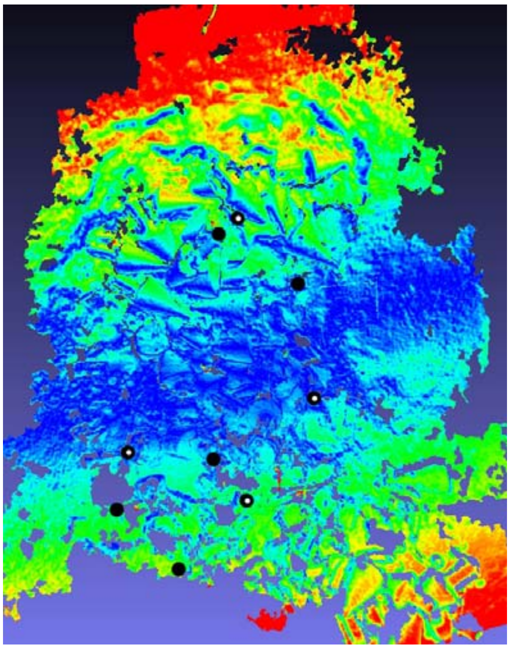

Figure 8: Visualization of registered point cloud accuracy. Differences among the same point cloud registered with different sets of control points, 4 and 9 respectively. Colour range from 0.002m (blue) to 0.075m (red). The quality of the registration is up to 0.02m within control points, while deteriorates rabidly on the outside (© D. Skarlatos, CUT & ARU, UCy, 2011).

4. RESULTS AND DISCUSSION

As in any scientific study, data gathering is of utmost importance. Since photogrammetry's raw data are photographs, one should pay particular attention to their quality. This is implied by the term "art" in the definition of photogrammetry. Unfortunately, photographic conditions are far from perfect in the underwater environment. Proposed methodology confronts problems regarding the layout and the automatic processing of almost any kind of photographs, leaving photographic quality as the major bottleneck of the process. In order to balance between unfavorable underwater photographic conditions, a number of tests were conducted using different lenses, flashes or no flashes and various distances. Since vertical and oblique photographs should be merged on a single bundle adjustment, variations in lighting due to flash, were causing problems in point transferring and therefore the use of flash was abandoned. It was further used only for archaeological documentation and/or when close up imagery had to be processed for small areas.

Photographs without flash were processed successfully by the software, but produced poor aseptically results on the final point cloud. Hence, photographs had to be treated digitally for color enhancement in order to achieve a balance between valid processing and visual acceptance.

In order to compare different color enhancement methods a photographic session of 61 photographs taken with the Canon 550D without flash was selected as test data. Photographs were digitally processed using different methods and gone through the proposed pipeline.

The 'enhanced contrast' data set was processed using ImageMagick functions to stress the contrast by clipping the original histogram by 1% on the lower part and 2% on the upper part. The 'neutralized' data set was processed using Adobe Photoshop and the neutralize function (figure 9). On the 'Wallis' data set, raw images were edge enhanced with the Wallis filter (figure 10).

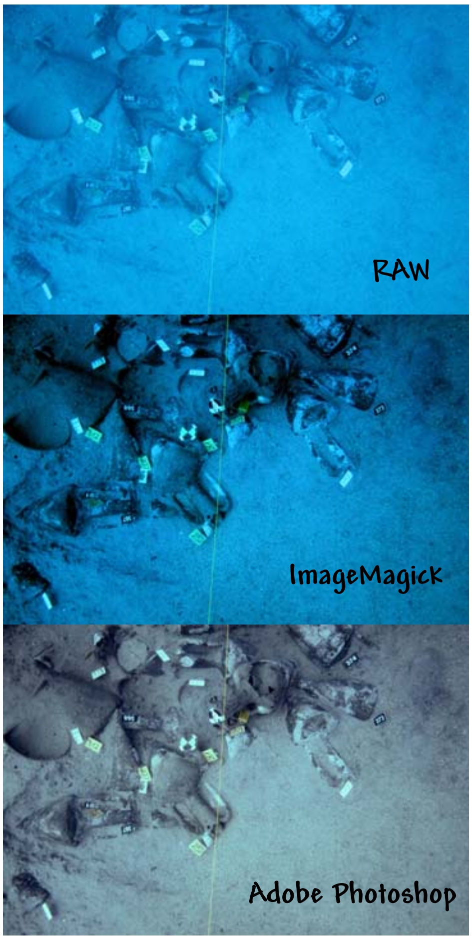

Figure 9: Raw image taken without flash and radiometrically enhanced images. Note the complete lack of red, which leads in almost greyscale-like images (photo A.Neofytou, © D. Skarlatos, CUT & ARU, UCy, 2011.

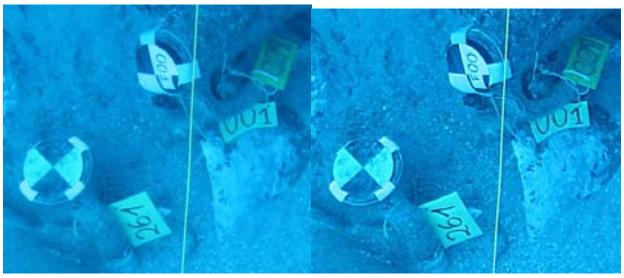

Figure 10: Detail from original and Wallis filtered image (photo A.Neofytou, © D. Skarlatos, CUT & ARU, UCy, 2011).

Bundler can handle self calibration independently on all photographs, but this isn't the case here, as focal lens was kept stable during photography. Since Bundler didn't have option to treat the data set accordingly, cameras were calibrated underwater using Bouguet's calibration toolbox and images undistorted externally. Bundler self calibration function was disabled and therefore was complied to use photographs with the given calibrated value of 3173.8 pixels. In all cases but this, the initial focal length was set to Bundler at 3400 pixels, with the self calibration function enabled. In such case all images are treated separately with different lens assigned to each one. SIFT and PMVS parameters were identical to all projects (pyramid level 1, cell size 2, threshold 0.7, window size 7 and min image number 3). At the georeferencing stage 7 control points were used. Results of this test are shown on table 11.

In all cases, the full set of the photographs was reported as successfully oriented by Bundler. Enhanced photographs, demonstrate better response to SIFT points, that the raw data set, as expected. Same response was expected from Wallis data set, but wasn't verified, since extracted SIFT points are significantly less. This fact was also verified by final correct matches after SBA, with Wallis showing results similar to raw rather enhanced data sets. Moreover, the number of final correct matches, means redundancy and usually good geometry, ensuring a more stable adjustment.

Mean reprojection error is the only value found within bundler output, that provides a measure of quality over the adjustment process. In all but the undistorted data set, this value was one pixel, implying good solution.

Since all images are treated with different focal length but return an individual value, the mean and the standard deviation were calculated as a measure of how well Bundler is performing on that aspect. Values close to 3173.8 pixels with low standard deviation are expected. All cases shown low standard deviation of 14-15 pixels (each pixel being 8.6um after image subsampling). Raw data is clearly closer to the calibrated focal length value, followed by Wallis, while there is a clear shift of 20 pixel values on the color enhanced data sets.

The number of iterations is a measure of convergence speed and stability. The enhanced contrast data set converges twice slower than the rest, without any further implications since it demonstrates similar final matches and mean reprojection error as the rest.

	Image data sets				
	Raw	Wallis	Enhanced contrast	Neutralized	Undistorted
Total images/ unused (Bundler)	61/0	61/0	61/0	61/0	61/0
Total key points (SIFT)	128,334	116,007	223,891	229,939	108,789
Total matches	249,955	192,506	357,145	333,145	208,222
Final matches (SBA)	14,896	13,362	26,805	26,922	9,273
Mean reprojection error [pixels]	1.0075	1.0444	1.0091	1.0192	1.4675
Mean estimated focal length [pixels]	3179.19	3185.96	3204.64	3201.56	-
Focal length STD [pixels]	14	14	15	15	-
SBA iterations	20	21	42	16	11
Point cloud [x 1000]	859	858	892	1001	543
σ_0 of georeference (m)	0.017	0.017	0.017	0.018	0.021

Table 11: Results from the comparison between different data sets, over the quality of BA, point cloud generation and registration quality.

The number of points in the final point cloud is a merit of image quality and content and enhanced images should perform better in that aspect. This fact was verified, as the neutralized data set, which had the most dense point cloud, was the most pleasant aesthetically as well. Raw and Wallis data sets had equivalent results.

Georeferencing accuracy was similar in all cases. Small deterioration in the undistorted data set can be attributed in the sparser point cloud and lack of points in the point cloud close to the control points.

Undistorted data set, should be examined separately as is poses a different case study. By using a valid calibration file from an external calibration (on the job) sequence and undistorting images prior to bundle adjustment process, one would expect better performance at least in bundle adjustment measures. Cross examination of the undistorted against the raw data sets proves that BA performs better but slower in raw data. Mean reprojection error and final matches are significantly better in raw data as well. More iterations in the raw data are justified by the fact that all images are being independently self-calirated, causing a slower convergence rate. The point cloud on the undistorted case is significantly inferior to the one with the raw data set. This can be attributed to small search area, internally adopted in PMVS software.

The fact that the undistorted imagery failed to perform according to the initial expectations, raises questions regarding the camera stability and reasoning for using a single calibration report. On the other hand computer vision techniques support multi camera self calibration, with very good results as indicated by the registration residuals. Therefore the camera calibration concept may need revision in such cases, where camera is placed inside a housing under 5.5 bar pressure, so its stability may be compromised and software should compensate.

6. CONCLUSIONS AND FUTURE WORK

The concept of developing a fully open solution in the shipwreck recording is attractive since:

- It can be adopted by any team anywhere in the world, regardless of the budget.
- It can be installed in many computers without any license portability problems.
- Elimination of constantly training personnel on different software adopted by different research teams. Personnel training on different software is no longer a constant need.
- It is a completely automated process that can produce 3D models, adequately fast.
- It can be customized by experts if necessary.
- Dense colour point clouds offer a comprehensive way to examine trench, while they can be used and analysed by non experts, without need to invest in extra software
- Its application requires minimum bottom time
- Photographic layout can easily be performed by inexperienced photographers while overshooting poses no significant problem in the processing phase
- It provides archaeologists who are familiar with photogrammetry and Photomodeler, the option to be trained in order to produce their own models without the intervention of surveyors. The proposed approaches at this stage are not mature enough yet, to be undertaken by inexperienced users.
- It can set a standard in the archaeological site mapping.

The results of the proposed method are impressive, but there are still minor issues to be resolved, before the process is completely fail safe. For example, underwater photography as means to get crispy and colourful photographs for photogrammetric processing is to be resolved in a case-to-case basis, as it depends on depth and equipment.

Fixed control point positioning and measuring is the bottleneck of the proposed method, at least in this particular study. A solution might be the adequately placement of flat cement blocks around the shipwreck. This would increase the area that should be covered in any photogrammetric dive but would ensure georeferencing. Nevertheless, securing the position of the cement blocks on a sandy seabed is an issue, mainly because the probability of unearthed artifacts lying in the immediate vicinity of the assemblage remains high. Moreover, measuring these fixed control points would be still a difficult task since currents, depth, diving time limitations and exposed amphora concentrations protruding high between the points do not favour tape measurements.

Any potential of wide application of the proposed methodology depends on the willingness of the archaeological team to invest in adopting new technologies that they could perform on their own, and therefore reduce cost and dependence on surveyors and architects for the mapping of their sites. Cost, complicated mathematics and the use of specialised hardware should not be used as excuses in the future.

AKNOWLEDGEMENTS

Authors would like to thank Cyprus University of Technology for the starting research grant titled "More Information". They would also like to thank all members of the excavation team, with the help of whom the results of the Mazotos project could not be successful. Particular thanks are owed to the surveyors of the photogrammetry team, Lena Diamanti, and Elli Stathopoulou, and to the divers who did the photography Antonis Neophytou, Markos Garras, and Jose Casaban.

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