A multi-camera system for the integrated documentation of Underwater Cultural Heritage of high structural complexity; The case study of M/S Helma wreck

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Abstract: High structural complexity is quite common in underwater archaeological sites and perhaps on top of the list when it comes to challenges regarding 3D reconstruction. Advances in underwater robotics and optical sensors are providing solutions for high quality data acquisition for mapping and documentation of underwater cultural heritage (UCH) sites. This paper presents a workflow for the detailed 3D reconstruction of a disintegrated shipwreck from the 1920's in Trondheimsfjord, Norway, a wreck site of high 3D structural complexity at 55 meters depth. The work focuses on the use of seven multi-purpose optical sensors, like low-cost action cameras, omnidirectional cameras, a depth camera and an RGB camera attached to an Underwater Hyperspectral Imaging sensor, all mounted on a Remotely Operated Vehicle (ROV). The 3D reconstruction of the wreck site was carried out offline, through the implementation of a typical Structure-from-Motion pipeline. Only one camera, considered as the master camera of the system, was connected to the ROV's control system and to the navigation sensors, hence providing georeferenced images. With the assumption that all seven cameras were moving jointly in 3D space, an approach for estimating the relative positions of the six stand-alone cameras, with respect to the master camera, was followed. The geometric configuration of the multi-sensor system allowed scaling and georeferencing of all created 3D models, and a more rapid alignment process of the big amount of collected imagery data. The presented case study highlights the advantages of multi-vision setups for UCH documentation, such as near 360° field of view with robust geometry; full 3D coverage of challenging objects of interest; the possibility of sensor's synchronization invariant approaches, and not least minimization of maneuvering and bottom time.

Keywords: underwater robotics, marine archaeology, optical sensors, multi-camera, system calibration, underwater photogrammetry, 3D reconstruction

1. INTRODUCTION

The need for fusing multiple sensors within one platform's frame for more efficient mobile mapping and 3D modelling is a widely studied subject. Since optical sensors can derive 3D information maxima in terms of resolution, accuracy and texturing that outperform e.g. sonar or Lidar (Ødegård et al., 2016), the use of multiple cameras on various types of platforms, in aerial, land and underwater domain has gained a lot of interest. Besides, in confined environments such as indoors, caves, or areas of high structural complexity, where an imaging platform cannot execute daring manoeuvres, the use of multi-capturing systems is a mitigating solution.

In archaeological projects in challenging environments at increased depths or zero visibilities, where human operations are limited, underwater robotics are recruited for exploration, inspection, documentation (Sørensen et al., 2020). Unmanned Underwater Vehicles (UUV) can facilitate the mounting of multiple sensors, combined towards this direction. The development of a unified network of sensors on a marine platform is usually a customized procedure that follows the needs of the target survey. In cases of 3D reconstruction of large and complex underwater scenes, like wrecks or reefs, a network of optical sensors on an UUV can address crucial issues like limited bottom time, the difficulties in manoeuvres and approach, the extended areas, the blind spots and occlusions and the acquisition of large amount of data. Multi-vision offers the capability of extension of the visibility range in environments where insufficient illumination, light attenuation, turbidity and low visibility are dominant conditions and provides redundancy in 3D reconstruction parameters. The effectiveness of such multi-vision systems in documentation of underwater cultural heritage is inextricably linked to an optimal path planning and a consistent joint extrinsic calibration. On the same idea, an almost fully automated path planning for the survey can be achieved, preferably with a more compact, low-cost ROV, with higher ease of maneuver, but still with almost equal risk of entanglement.

In January 2021, marine scientists from NTNU launched a scientific cruise in Trondheimsfjord in order to collect data from various sites of interest, among which the Tautra Coral Reef, a Halifax WWII bomber aircraft wreck and the Skogn shipwreck. The base of operations for the cruise was NTNU's research vessel (R/V) Gunnerus which is equipped with a suite of underwater vehicles and sensors, capable of high resolution seabed mapping. Within the framework of the project presented here, a SUB-Fighter 30K Remotely Operated Vehicle (ROV) was used, with a custom payload of navigational and "multi-purpose" optical sensors with respect to the needs of a detailed and accurate 3D documentation of the Skogn wreck.

The term "multi-purpose" refers to the fact that the presented cameras setup, initially, was not formed exclusively for the geometrical documentation of the wreck site, but for various purposes. For example, the Underwater Hyperspectral Imager (UHI) was mounted on the ROV for the identification and mapping of biogeochemical objects of interest on the wreck (Røste, 2021), whereas the omnidirectional GoPro setup was provided by Stargate Media AS for filming and outreach purposes. This paper presents a workflow for a strategical exploitation of multiple cameras towards enhanced mapping capabilities for a challenging wreck site survey.

Section 2 presents related work as a motivation for the proposed workflow. Section 3 describes hardware, configuration, processing, and briefly the wreck site used for the case study. Results from the case and evaluation are presented in section 4, including experiences from an archaeological end-user perspective. Finally, conclusions are given in section 5.

2. RELATED WORK

Multiple-camera systems calibration is an objective that concerns a wide cluster of works in literature, connected to mobile mapping, sensors fusion and 3D reconstruction. Focusing on optical sensors, a three-step calibration pipeline is mostly presented, starting with the calibration of each sensor for the estimation of their intrinsic parameters, then an extrinsic calibration for the group of sensors is held and finally an optimization step is performed for the refinement of the extrinsic calibration. This general path is followed in the present work, with the substantial differentiation that due to lack of synchronization of cameras, the second step is approached geometrically through the bundle adjustment of all cameras within a common reference frame and the implementation of an alignment algorithm for the estimation of the relative position of each camera in the system.

On this direction of geometry-based approaches, Yamazoe et al. (2006) suggested a calibration of many cameras, in which, camera parameters and 3D points of a target object are simultaneously optimized within a bundle adjustment, by minimizing the reprojection errors between the 2D image coordinates and the 3D world coordinates of the object. Le and Ng (2009) operate a joint calibration of multiple sensors, introducing an objective function that splits the entire group into sub-groups of "sharing" sensors, calibrates each sensor individually and then calibrates as many sub-group combinations that can produce 3D data as possible, thus increasing system's robustness. Chen et al. (2013) proposed a multi-camera system, consisting of four synchronized CCD cameras, which considers any two cameras as a stereovision system. Each stereovision system is calibrated independently providing 3D measurements of areas that are overlapping among the subsystems. The final 3D reconstructed object gathers all stereovision systems into a universal one, deriving their relative positions. OpenPTrack (Munaro et al., 2016) is an open source software for calibration of synchronized multi-camera setups aiming for people detection and tracking. People detections are used for camera poses refinement and the system is able to fuse data coming from many sensors.

In the underwater domain, Nocerino et al. (2018) presented a method for the synchronization and calibration of a multi-camera system, composed of eight action cameras mounted on a low-cost ROV for the 3D mapping of underwater caves. Their approach emphasizes equally on the accurate calibration of the intrinsics of each camera, as well as on the computation of the relative orientation (RORE) parameters between all cameras. The lack of accurate synchronization for all cameras was faced by the authors through a repetitive event of flashing lights in complete darkness and measuring the median intensity values of the event in each dataset. Jhan et al. (2020) introduced a project of object tracking from a system of multiple cameras deployed underwater for the inspection of a steel pipe installation. They experimented on single- and multi-camera calibrations, both in air and underwater, concluding that the single-camera approach derives reliability in measurements as well as cost effectiveness and less computation complexity, compared to the multi one. Rofallski et al. (2020) proposed a multi-sensor system, consisting of three industrial-grade cameras mounted on a low-cost ROV in order to monitor artificial reefs in Western Australia through photogrammetry. Their approach entails a self-calibration procedure for the estimation of relative orientation of the cameras, by rotating the system around all axes and observing predetermined targets of known geometry. Besides the system's calibration, this work focused also on image processing and masking techniques for optimizing the SfM processing. Pacheco-Ruiz et al. (2019) presented the 3D photogrammetric recording of a 4^{th} century BC shipwreck of high structural complexity at 2,122 meters depth in the Black Sea. Using of a work class ROV and a SROV (Surveyor Interceptor), both equipped with cameras and lights, they followed predefined trajectories in the perimeter of the wreck. The authors do not refer to a certain calibration formula for the group of cameras used, but the initial values of the camera poses for the photogrammetric modelling were derived by the navigational data of the central control system of the vehicle that each camera was subject to. Recently, Xanthidis et al. (2021), proposed an active perception framework for UUVs equipped with multi-camera systems, which allow a safe navigation of the vehicle, while actively tracking multiple visual underwater targets. They mention the effective dealing with limited fields of view (FoV) and ranges, whereas they discuss the potentiality of extending their approaches to multiple-sensor configurations, adding sonars or LIDARS. Among others, they experiment with their method in the environment of a shipwreck of complicated 3D geometrical volume.

3. PROJECT WORKFLOW

3.1 Underwater Vehicle & Sensors

The SUB-Fighter 30K, a light work class ROV, designed by Sperre AS, was deployed from R/V Gunnerus for the documentation of Skogn wreck (Fig.1). It gets power from and communicates with the surface vessel with a 650 m umbilical and all operational systems, such as control system computers, power supply and monitors, are fitted inside an on-board container (Nornes et al., 2016). For this survey, the ROV's combined stereo camera (two Allied Vision GC1380C cameras) was replaced by the customized multi-camera system described below. Two HMI lamps mounted on the top front bar of the ROV mitigated the loss of ambient light at 55 meters depth. Due to the high structural complexity of the shipwreck and the size of the vehicle (240 x 104 x 142 cm), navigation through every part of the wreck and especially through bow and stern areas was challenging. The ROV was piloted mainly manually, using a joystick console, to follow planned trajectories based on a 3D model of the site from a previous mission. The ROV is equipped with a Kongsberg High Precision Acoustic Positioning system (HiPaP 500), a Doppler Velocity Logger, an Inertial Measurement Unit and a pressure sensor. All data from the navigational sensor logs were processed for extracting the accurate underwater positions of the ROV's trajectories. More details on the high-accuracy estimation of underwater position using this navigational suite can be found in Dukan et al. (2013).

Fig. 1. Deploying SUB-Fighter 30K for the documentation of Skogn wreck.

The multi-imaging system mounted on the ROV consists of 7 RGB multi-purpose cameras in total; an omnidirectional system of three GoPro cameras, an individual 45°-looking GoPro camera (Fig. 2), a down-looking ZED stereo RGB-D camera and a compact RGB camera co-registered to a UHI scanner. All cameras are capable of recording at high frequencies, thus offering the capability of generating as dense frames as possible from the video recordings. This is a prerequisite for the global calibration of the multi-camera system described next. The only sensor that was synchronized to the ROV's control system and respectively to the navigational data is the UHI one. The lack of synchronized timestamps for all the sensors led to an approach based mainly on geometrical constraints, considering the UHI-RGB camera as the master - or reference - camera and the other cameras in the system as slave cameras. All cameras were placed almost in the front of the ROV, apart from the UHI-RGB which was placed in the middle, so that an adequate overlap in their field of views could be attained.

Table 1. Camera types used

Camera	resolution	fps	synchr
Single GoPro	2704x1520	60	-
3 x GoPro (Omnidirectional)	2704x2028	30	-
ZED stereo	1920x1080	30	-
UHI	648x486	20	✓

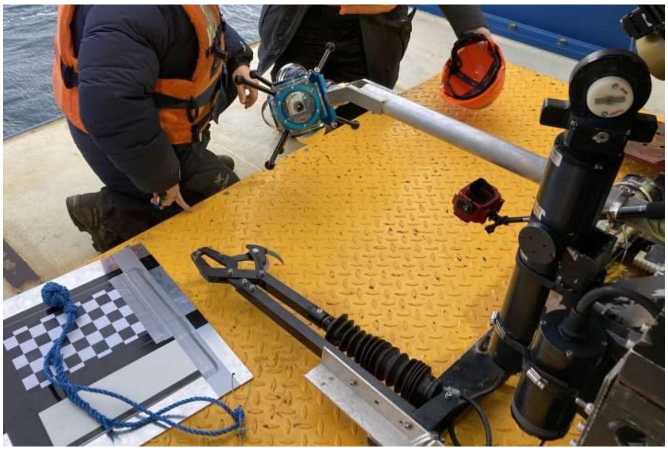

Fig. 2. Setting up the multi-cam system. An omnidirectional system of six GoPro cameras and an individual GoPro are mounted in the front of the ROV, facing different perspectives of the seabed and the wreck. The chessboard pattern was used for the intrinsic and extrinsic calibration of each camera.

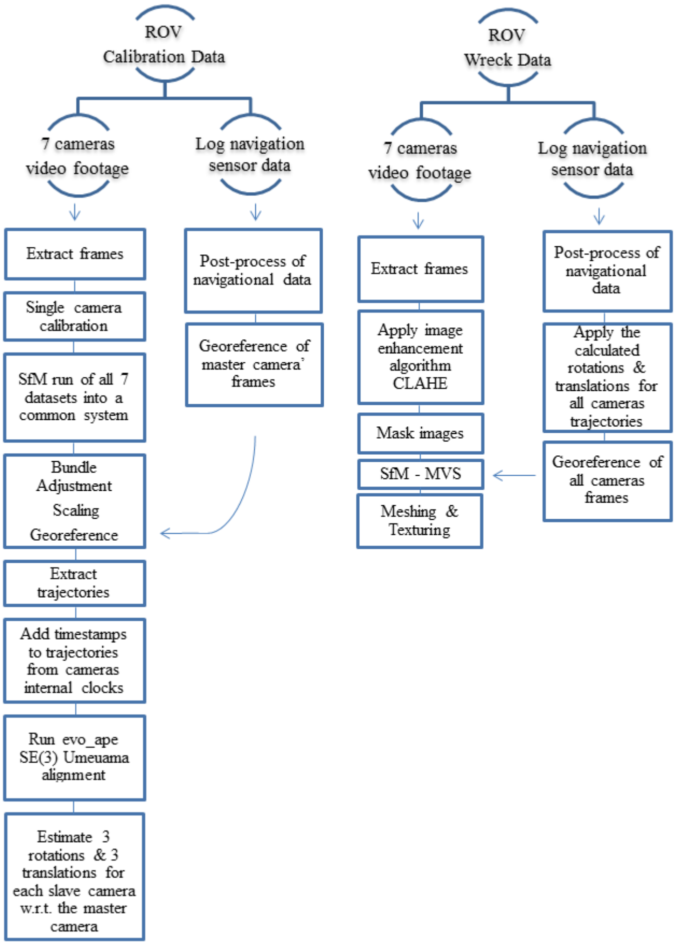

Fig. 3. Methodology workflow. Left: From ROV calibration data acquisition to calculation of relative positions of all cameras in the system. Right: From ROV wreck data acquisition to the final 3D reconstruction of the site.

3.2 Individual camera calibration

For the needs of both types of calibration, single and global, a chessboard was placed on the seabed by the ROV in the area of the wreck site as a calibration target of a precise fixed-size pattern. The ROV moved along a path that crossed the calibration board and rotated (about the yaw axis) so that the imaging system could observe the calibration board from various angles and distances, confirming that the pattern was visible for the cameras and if not by all at the same time, at least in pairs. From this calibration dataset, key frames were extracted from each video sequence, in a common frame rate and the best quality images in terms of sharpness and geometry were picked.

At first, all cameras were calibrated separately for the estimation of the camera parameters (intrinsics, extrinsics and distortion effects) of each sensor. The intrinsic and extrinsic calibration for each camera was performed in "Camera Calibrator" Toolbox of Matlab (Bouguet, 2004). Since the calibration dataset was acquired in situ, any additional errors due to refractive index or other parameters were considered negligible (Rofallski, 2020). Within the framework of this project, the omnidirectional system of the three GoPros was treated as a system of three synchronized identical cameras that were calibrated separately for the intrinsics of each camera. Due to the redundancy of 3D information acquired by the wide overlap of the omnidirectional system of GoPros with the rest of the cameras, the current work did not emphasize on estimating parallax errors coming from short baselines camera systems like an omnidirectional one (Bosch et al., 2019).

3.3 Multi-camera system configuration

For the extrinsic calibration of the multi-camera system, it is assumed that all sensors are mounted to a rigid body and move jointly in 3D space. Unlike the intrinsics estimation, the system's extrinsic calibration implies all cameras at once, since it is solved by the simultaneous capture of images of the calibration board by all cameras, when the imaging platform moves around it. In our case, due to the lack of synchronized timestamps for all sensors, the extrinsic calibration was based on geometrical constraints. A typical Structure-from-Motion pipeline was performed in Agisoft Metashape software. After the final optimization of the bundle adjustment during the relative orientation of the chessboard images, a trajectory was estimated for each camera. The common frame rate for all cameras, regarding the frame extraction from the video sequences was set to 3 fps. The video frames were extracted with the use of the open-source software FFmpeg (FFmpeg Development Team, 2010).

After its global alignment, the block of images was scaled and georeferenced thanks to the ROV's navigational data and the georeferenced trajectory outputs of all cameras were extracted. The internal clock of each camera was used in order to add a timestamp to all video frames. The roughly synchronized timestamps were adequate enough for the initialization of the next step. EVO python package tool (Grupp, 2017) was then implemented for the calculation of the rigid body transformation matrices (3 translations and 3 rotations) of each slave camera with respect to the master one. Scale was fixed thanks to the photogrammetric bundle adjustment of all datasets into a common reference system. The transformation matrix for each camera consists of a translation vector $\boldsymbol{t} \in \boldsymbol{R}^{3x3}$ that refers to the displacement along X, Y and Z axes of the body coordinate system and a rotation matrix $\boldsymbol{R} \in \boldsymbol{R}^{3x3}$ that refers to the rotation angles along those axes, that is yaw, pitch and roll.

$$T = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \quad (1)$$

EVO is typically used for the evaluation and comparison of SLAM and odometry trajectories that refer to the same sensor. In our case, this comparison among trajectories is used to derive the relative positions of all cameras, by finding the corresponding nodes (video frames) of each trajectory to the master one (Fig. 4).

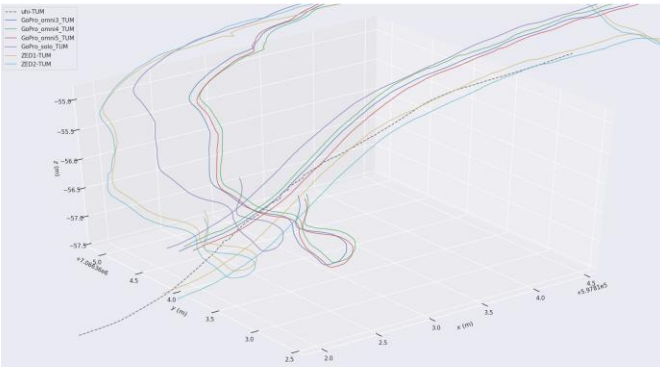

Fig. 4. Multi-camera system calibration dataset: trajectories for each slave camera, overlaid with the dashed trajectory of the master camera that serves as ground truth. The computed displacement and rotational errors form the required transformation matrix.

On this purpose, the calculation of the six required parameters is achieved through the implementation of SE(3) Umeyama alignment that is integrated into evo_ape tool. This tool calculates the absolute trajectory error, providing also statistics for the global consistency of the trajectories (Fig. 5). The errors in translation and rotation are finally the required values of the transformation matrix.

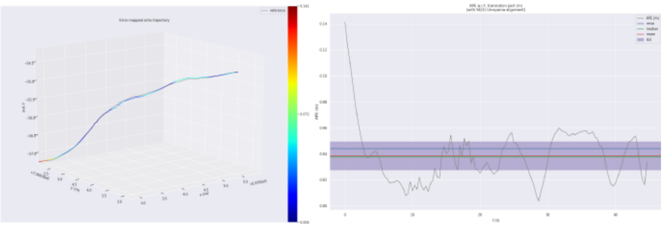

Fig. 5. EVO_ape metrics. Left: The error of the estimated trajectory after the alignment to the reference trajectory (master camera), visualized in 3D space. Right: the absolute pose error after the alignment.

3.4 3D reconstruction of M/S Helma

The wreck site M/S Helma was first detected and located by AUR-Lab off Skogn coast in Trondheimsfjord in 2014. A first archaeological survey of the site was conducted, using integrated underwater technology, including optical and acoustical sensors. A dataset of MBES, SSS and imagery data was collected by the researchers, creating the first maps and 3D visualizations of the wreck and its surrounding area, enabling the identification of the ship. M/S Helma was built in 1919 as a wooden three-masted motorized schooner, it was 38 m long, 8 m wide and 4 m high and according to sources (Tandberg, 1993), it burned down during the transportation of hay in 1927. Due to the fire, much of the wooden hull was burned away as expected, while the iron parts, like the boiler and the engine at the stern were preserved. Individual objects, such as a chip log and a lantern were also preserved, indicative of the marine equipment of that period (King, 2020). The current condition of the wreck as it is lying on the seabed, declares an area of high structural complexity with both horizontal and vertical elements. Ropes, wires, two or three masts, poles and other protruding objects makes the wreck a challenging environment for ROV based photogrammetric 3D documentation and reconstruction (Fig. 6).

For the needs of the 3D recording of the wreck site, the trajectories were planned according to the 3D models created from the previous season's mission. Based on these base models, the ROV was piloted manually due to the presence of many vertical and horizontal objects, especially in the bow and the stern. The ROV moved mostly around the perimeter of the wreck, taking advantage of the wide FoV capturing thanks to the multi-camera system. A flight over the midship which is mostly flat and free of obstacles was finally performed for the complete coverage of the site. Approximately 18 minutes of video footage were collected for the 3D recording of the shipwreck, cut into frames with a rate of 3 fps.

Due to diverse lighting conditions and image qualities of the different sensors, an image processing step for gaining a common radiometry among all data preceded the Structure-from-Motion processing. For this purpose, a Contrast Limited Adaptive Histogram Equalization (CLAHE) was applied on all image datasets, in order to improve a better and more uniform quality of the underwater images. An automated masking step was also implemented in certain datasets and specifically in cases of images, whose parts of their frames were covered by ROV elements like lever-arms.

Given the 3D rigid body transformation matrices for each slave camera with respect to the master one, camera poses of each trajectory were pre-computed and used as reference data for speeding up the global orientation of images (Fig. 6). After a conventional SfM-MVS workflow in Agisoft Metashape software, the dense point clouds and textured 3D meshed models of the M/S Helma shipwreck were created.

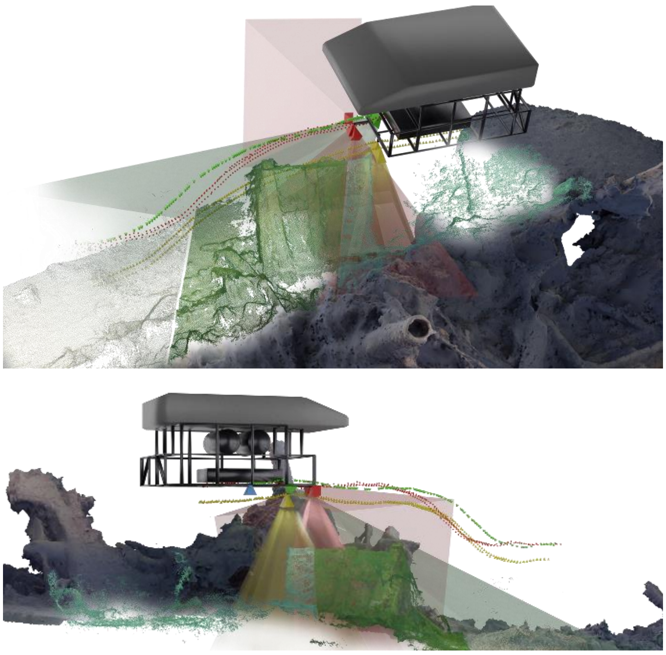

Fig. 6. Perspective views of the trajectories (red, green, yellow) of the multi-camera system, their fields of view and the respectively created point clouds. The 3D model of the

30K ROV is conceptual and does not respect the real proportions.

4. RESULTS AND EVALUATION

During the configuration of the multi-camera system and the estimation of all cameras relative positions in the system, evo_ape tool was used for the estimation of the absolute pose error between the camera poses of the reference trajectory (master camera) and the estimated trajectories (slave cameras). For the initialization of the error estimation process, the association of the estimated poses to the ground truth poses was achieved through timestamps of the internal clock of each camera. Based on this association, the reference and estimated trajectories were aligned and output the mean, median and standard deviation of the differences for each camera pose. From the collected calibration data, this alignment was implemented for each slave camera of the system and the average of the root mean square error was approximately 0.04 m.

Approximately 12,000 images, cut out as frames from the videos of the multiple cameras, were aligned and georeferenced, thus permitting a correct scaling and location of the wreck model. The RMS after the bundle adjustment was sub-pixel for the image's orientation and $\approx$ 2.5 cm in XYZ. The 0.04 m residual from the alignment process within evo tool was reflected to a finally low reprojection error during the relative orientation of all images. A low RMS, both for relative and absolute orientation, after the final bundle adjustment, was achieved thanks to the redundancy of the input imagery data. Considering the fact that the motion of the vehicle was quite slow and the 3 fps rate is considered quite frequent, resulting to dense trajectory nodes, the extrinsic calibration of the system provided reliable results.

Close related works on mapping of underwater structures with the use of more than one visual sensor (Pacheco-Ruiz, 2019; Xanthidis, 2021) are benefited by the synchronization within a common control system or by a prior knowledge of the geometry of the structure that simplifies human or robotic operations. The aforementioned results confirm that the presented approach can be effective in cases of lack of synchronization or prior geometric knowledge of the object of interest, thanks to the reduced maneuvering and the increased global FoV. Additionally, the system calibration pipeline boosted the 3D reconstruction phase significantly in terms of automation and processing time.

Due to the inherent uniqueness of shipwrecks, quantitative comparisons of results from documentation at different sites are rarely suitable. However, based on experiences from wreck surveys with similar challenges, e.g.in Mogstad et al. (2020) the advantages in terms of effectiveness of the setup and workflow presented here are apparent.

5. CONCLUSIONS

Site formation processes that are typical for UCH deposited in seawater are likely to produce "flat" wrecks with little remaining structural integrity. However, a consequence of the 100-year age used to define UCH by e.g. UNESCO (Dromgoole 2014), is that an increasing number of metal wrecks falls within this category. They typically have a higher degree of structural integrity, and hence represent more complex objects for 3D documentation and reconstruction – both regarding data quality and coverage and safe operations. This paper presents the results of the 3D recording of a 1920's shipwreck of high structural complexity with the use of a multi-camera system, mounted on an ROV. The considerable overlap of the cameras' FoV encourages a full 3D reconstruction of a challenging wreck site with limited bottom time. It is shown that the workflow using robust extrinsic system calibration speeds up the aligning process, while conveying scaling and world coordinates reference to the 3D reconstructed models. An additional upside is that less maneuvering of the platform is required to ensure full scene coverage, reducing the risk for entanglement, or collision with and potential damage to heritage objects outside the pilot's FoV. Adjusting arbitrary multi-camera configurations on more compact underwater vehicles could facilitate the ease of use and the maneuverability in confined environments even more. On the other hand, compact sensor-carrying platforms require more investigation on the accuracy and robustness of the system calibration, due to the short baselines of the sensors.

We suggest further research into transferring such a geometry-based approach to online processing would enable the implementation of real-time algorithms for navigation and mapping, like Simultaneous Localization and Mapping

Fig. 7. Photorealistic 3D model of the wreck site, created by fusing imagery data of two surveying periods (2019, 2021).

(SLAM), as well as Visual Odometry algorithms, thus offering the capability of a higher degree of control of the vehicle's motion in a challenging environment, while reaching at the same time an optimal 3D coverage.

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