Close range underwater photogrammetry for high resolution survey of a coral reef: A comparison between reconstructed 3-D point cloud models from still image and video data

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Abstract: Coral threat levels from climate change have increased around the globe. Coral reefs are nature's best coastal protection device [MS48]. They dissipate portions of the wave energy through a system of multi-scalar tunnels to gradually reduce the power of large swells. As complex and permeable underwater structures, reefs refract waves instead of reflecting them which results in sand deposition instead of erosion [GP17]. Currently reefs are threatened around the globe because of rising sea temperatures due to global warming, elevated levels of CO2 from pollution acidifying the oceans and radical practices such as dynamite fishing. Architects study their geometry to develop artificial coral reef systems to regrow premorse parts of corals and coastal protection devices [Vo18]. To understand the reef geometry detailed surface configurations and textures of a natural coral reef, a workflow was developed for close- range underwater coral reef monitoring that outputs high precision 3-D point cloud models. Utilizing the case study site of Gili Trawangan, Indonesia, underwater data from high- resolution still image and video data was collected of a natural coral reef and 3-D reconstructed precise point cloud models from both datasets. In this paper both reconstructed point cloud models are presented and results from underwater photo- and videogrammetry are compared followed by discussing the potential of both methods for close range underwater survey. The accuracy and reliability of both techniques by measuring objects of known size is demonstrated.

Keywords: Close- range underwater photogrammetry, underwater video-grammetry, coral reef monitoring

1 Introduction

1.1 Why do architects underwater survey coral reefs?

Coral reefs form excellent study objects for the exploration of high-resolution 3-D scanning and modelling methods. They are geometrically and structurally complex and present many challenges regarding 3-D scanning and modelling of their intricate surface configurations [VSW19]. In this section, I introduce two 3-D surveying methods to capturing 3-D models of a natural reef at close-range used during my field research in Gili Trawangan in Indonesia: underwater photogrammetry (UW photogrammetry) and underwater videogrammetry (UW videogrammetry).

- Photogrammetry multiview 3-D reconstruction, or Structure-From-Motion (SfM), is a technique for constructing three-dimensional structures from two-dimensional imagery from images.

- Videogrammetry is a measurement technique based on the principles of photogrammetry [Gr97]. Instead of still images it uses extracted image frames from video footage.

I used both methods to retrieve information of high resolution underwater images and videos to recover the exact three-dimensional position and colour of surface points of a natural coral reef. The principle of underwater photogrammetry does not differ from that of terrestrial or aerial photogrammetry but it is necessary to take into account certain elements that may cause disturbance, in particular the refraction of the diopter water-glass and the presence of the housing [BLL02]. One major influence on the quality of 3-D reconstructed models from photo- and videogrammetry is visibility, a measure of the distance at which an object can be distinguished [SB81]. Underwater vision is limited by large numbers of individual invisible particles dissolved in the water. Image and video data collected at a low visibility of less than 10 meters shows poor alignment rates in image processing software [VSW19]. UW photogrammetry equipment is financially affordable, transportable and can be handled by only one diver. Underwater photo- and videogrammetry for underwater surveys are currently under investigation in Archaeology, Geology and Marine and Conservation Biology. Since 2014, Hydrous, a U.S. based non-profit organisation has created the campaign, 'open access oceans' for engagement with marine environments, collecting underwater image data for use in close-range underwater photogrammetry of natural coral reefs around the world. These models are clean 3-D polygonal mesh models and textures of different coral topologies and exploited as Open Access Models on SketchFab, an online 3-D content library [Sk19]. The resolution in this library is less precise than in this approach presented. In April 2016 the French section of Reefcheck, a non-profit organization dedicated to the conservation of tropical coral reefs, used a GoPro Hero 4 Black to 3-D reconstruct a 305 m2 coral reef near Reunion Island from 1625 video frames extracted from video footage. Their goal was to identify bleached areas of the reef through a digital textured surface model of the reef [Pi16]. Their resulting 3-D surface models lack in details regarding the exact geometry of individual corals species. However, rebuilt textures are of low resolution and show poor resolution in areas where surface geometry becomes more complex.

1.2 The case study coral reef in Gili Trawangan, Indonesia

The case study object is a natural reef at a depth of approximately 13 meters, about 100 meters off the shoreline of Gili Trawangan island in Indonesia. The reef is 100 cm long, 100 cm wide, and at its highest point, 80 cm high. The goal for the experiments was to achieve high precision rates of 1-5 millimeter for 3-D models from UW photo- and videogrammetry. In this paper, the unique underwater workflow at close range for high accuracy 3-D models of corals using UW photo- and videogrammetry is proposed. Precision values for both reconstructed 3-D point cloud models from (i) still images and (ii) video footage with 25 manual UW measurements of the reef are compared. Survey results demonstrate a high level of detail, completeness of the overall model, reliability and application in the field for both methods. Based on evaluation the deployment criteria for each underwater survey method is then proposed.

2 High precision methods for 3-D reconstruction from UW Photo- and Videogrammetry

After a general introduction of the survey technology used, this section focuses on the implementation and validation of UW photo- and videogrammetry. During underwater field survey in Indonesia, the focus was on a complete 3-D scan of a natural reef with the Canon EOS 5Ds camera system. This camera system uses one of the best image sensors (50.6 megapixel) and highest output resolution (8688 x 5792 pixel) on the current market. Together with a Canon 50 mm 2.5 macro lens inside of a SEACAM underwater housing 5DMKIII, two SEACAM strobes (SF150D) and one video light completed the system. The camera system has the capacity to optimize sharpness and clarity of high-resolution images through a low-pass cancellation filter. This unique feature lowers the risk for digital artefacts in photographs. The macro lens was selected to prevent image distortion.

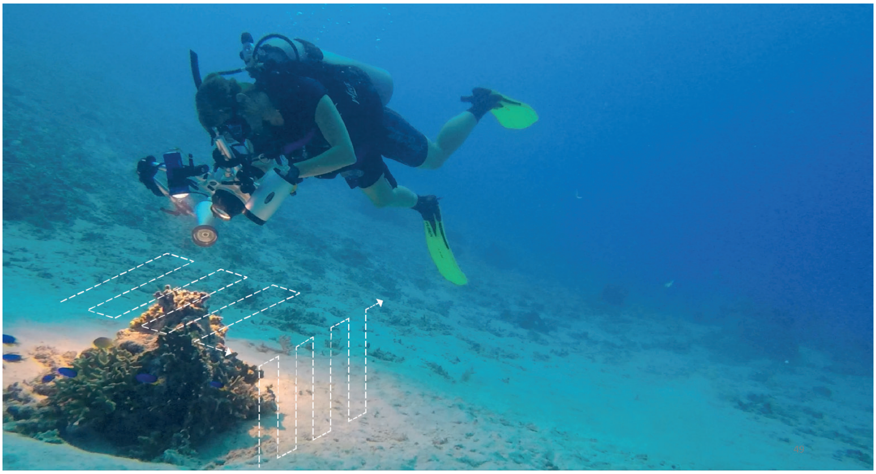

Figure 1: Getting ready to videoscan a natural coral reef in Gili Trawangan, Indonesia, following a lawn-mower pattern using Canon EOS 5Ds.

Two complete datasets of a natural reef were collected one from 1260 high-resolution still images (8688 x 5792 pixels) and the other one from 912 extracted frames from video footage (1920 x 1080 pixels) (Table 1). Stills and videos were taken at a distance of 25- 40 cm between camera and object following a so-called “lawn-mower” photogrammetry pattern with 60 % of side and 80 % of forwarding overlap (Figure 1) [Ag18]. Camera settings such as aperture value, ISO number and image resolution were kept constant respectively for each dataset. PhotoScan Pro Version 1.4.4 (Agisoft) image processing software was used to reconstruct 3-D point cloud models. Both datasets (DS1 and DS2) were collected at a visibility of approximately 30- 35 meters.

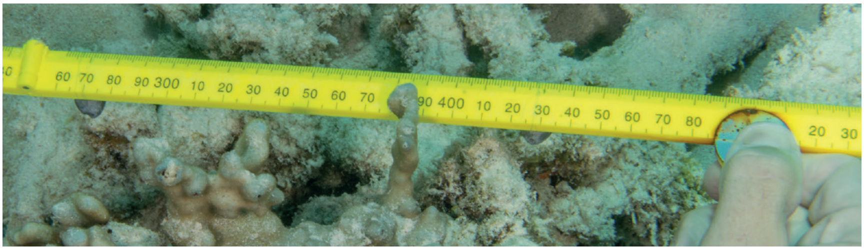

Figure 2: As a reference for the original size of the natural reef, we took about 25 manual measurements to scale both reconstructed 3-D point cloud models and to calculate deviations between the original and digital reconstructed 3-D model.

Table 1: Technical data for 3-D reconstruction experiments from still image and video data.

Canon EOS 5DS R	Still image data (DS1)	Video data (DS2)
File format	JPEG, RAW	MPEG
Resolution	8688 x 5792 pixels	1920 x 1080 pixels
Light source	Two SEACAM strobes (SF150D)	One video light
Underwater battery life time (camera and light source)	Camera 70 min, SF150D strobes at 25 % approx. 800 still images	Camera 50 min, video light at 100 % approx. 35 min

2.1 UW Photogrammetry 3-D point cloud model

The still image data from DS1 was processed in PhotoScan Pro Version 1.4.4 and the resulting point cloud model cleaned in Cloud Compare V2.10.1, an open source 3-D point cloud and mesh processing software [Cl17]. 25 manual measurements from around the model were then compared with measurements taken from the scaled digital point cloud model and calculated a precision for the final 3-D point cloud model of a range between 2 to 9 mm. The final point cloud model is complete and displays high detail of the geometry and texture of corals (Figure 3-8).

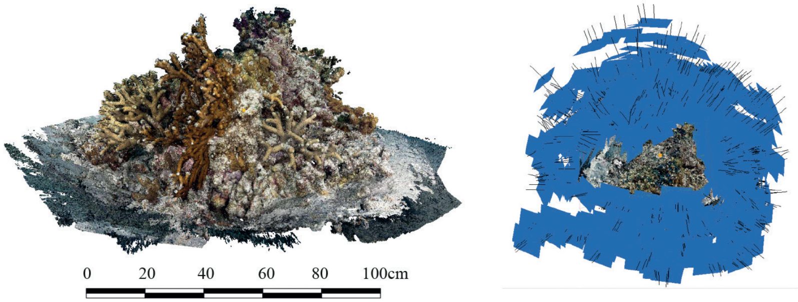

Figure 3- 4: Overall point cloud model reconstructed from 1260 still images (DS1) with camera positions. The model has 621,912,135 colored points.

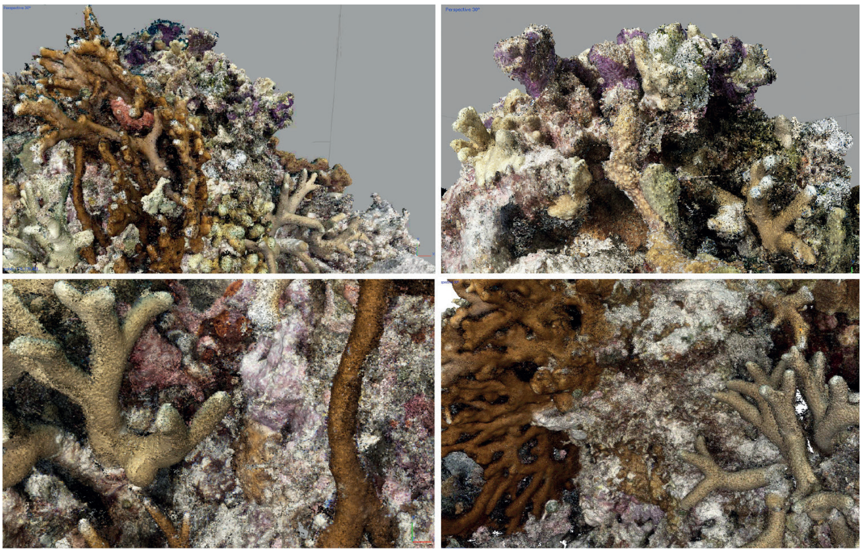

Figure 5- 8: Resulting details of reconstructed UW photogrammetry point cloud model (DS1) from still images.

2.2 UW Videogrammetry 3-D point cloud model

The second model 912 video frames (1920 x 1080 pixels) were extracted at a frame extraction rate of 15 frames per second (fps) from DS2. Following the lawn-mower pattern method, the top, left, right, back and front faces of the natural reef were captured in five video files. Extracted frames had the correct image overlap between 60 % and 80 % to be aligned and processed in PhotoScan Pro Version 1.4.4. The results were cleaned and scaled to the resulting point cloud model in Cloud Compare V2.10.1 and calculated deviations of a range between 7 to 25 mm. The overall 3-D model is complete from all sides, but has several holes (Figure 9).

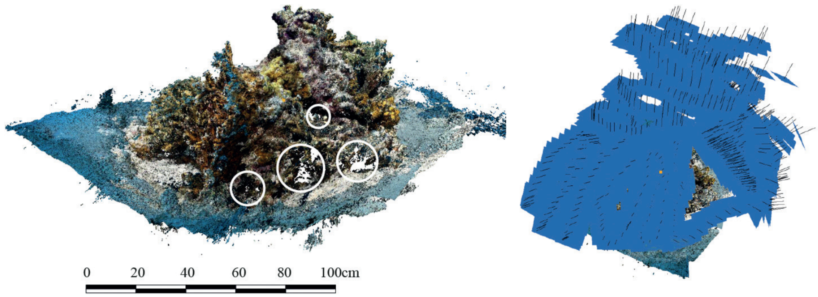

Figure 9- 10: Overall point cloud model reconstructed from 912 video frames (1920 x 1080 pixels) (DS2) with camera positions. The model has 74,505,524 points.

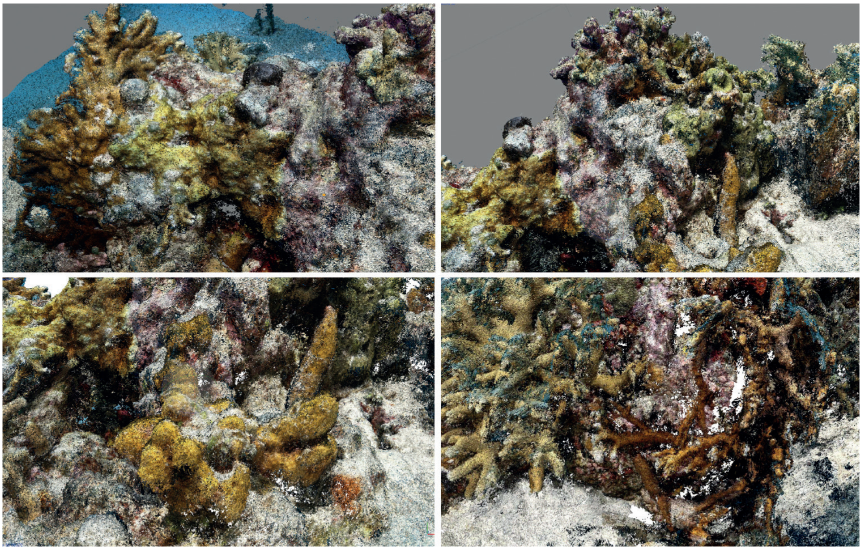

Figure 11-14: Resulting details of reconstructed UW videogrammetry point cloud model (DS2) from extracted video frames.

3 Results and discussion

3.1 Comparison of results from UW Photo- and Videogrammetry

The comparison criteria of both methods is precision, level of detail, model completeness in the resulting point cloud model and overall time to generate a 3-D model. Both datasets, from UW photo- and videogrammetry reconstructed 3-D point cloud models describe the overall surface of the scanned coral reef. Our reconstructed 3-D model from UW photogrammetry is cleaner and describes in high detail resolution and colour the scanned geometry of individual corals (Figure 5-8). This can be attributed to the high resolution input data from still images of 8688 x 5792 pixels, as well as, razor-sharp and perfectly illuminated images. Therefore, UW photogrammetry is a more reliable method to reconstruct highly accurate and complex 3-D models from UW data at close range than UW videogrammetry (Figure 15-18). UW data collection and image processing took much longer for our UW photogrammetry models than for UW videogrammetry models. Data collection in the field for DS1 took twice as long as for DS2. Model processing time in PhotoScan Pro Version 1.4.4. took 8 times longer for DS2 than DS1. Even though the point cloud model from video frames is less precise, UW videogrammetry is still a convincing method to quickly capture the overall geometry and texture of the test coral reef with an average precision of +/- 7 mm (Figure 11-14). An average precision of +/- 3.5 mm for the 3-D model was calculated from DS1 (Figure 15-16). Both, UW photo- and videogrammetry have the potential to monitor complex underwater landscape models at high precision and are applicable. In commercial environments greater financial resources are available.

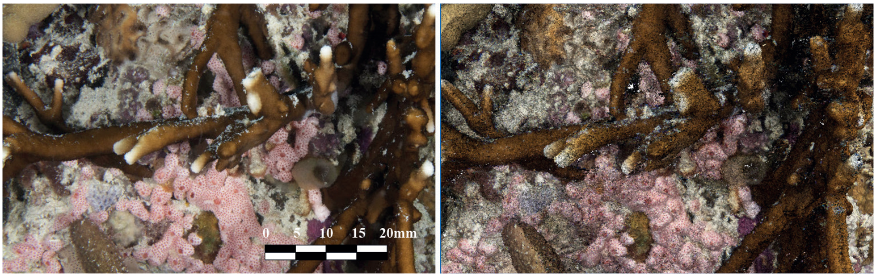

Figure 15-16: UW photograph (left), screenshot of 3-D point cloud model from DS1 (right). This enlarged view of the 3-D model represents one of the more complex areas of the scanned reef.

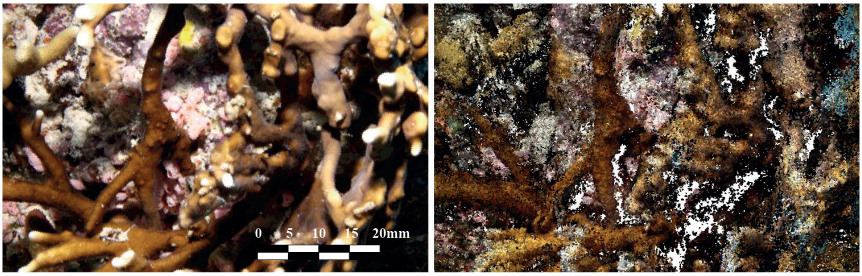

Figure 17-18: Extracted frame from UW video (left), 3-D model from DS2 (right). This view shows the same region of the scanned reef as in Figure 15-16.

Table 2: Technical details for 3-D reconstruction of point cloud models from image and video data.

	Reconstructed point cloud model from still images: Dataset 1 (DS1)	Reconstructed point cloud model from extracted video frames: Dataset 2 (DS2)
Total number of images/ videos	1260 still images	912 extracted video frames (15fps)
Time to collect data/ Number of dives	2 dives/ in total 75 min	1 dive/ 20 min
Number of partial models	2 partial models (2 chunks[1])	1 partial model (1 chunk)
Alignment rates	Chunk 1: 603 of 618 (97,6 %) Chunk 2: 619 of 642 (96,4 %)	Only 1 chunk: 912 of 912 (100 %)
Processing time of dense cloud	Chunk 1: 3 days and 21hours Chunk 2: 3 days and 13 hours Total: 4 days and 9 hours	23 hours and 32 minutes
Number of points overall model	621,912,135 points	58,498,527 points
Precision of 3-D model[2]	+/- 2- 5 millimeter	+/- 7- 15 millimeter
Detail and completeness of model	High detail of overall model and individual corals	Overall geometry was reconstructed, low detail of corals, model has holes

[1] In PhotoScan Pro, chunks allow to include similar image and video data in one dataset. Several chunks can be included in the same file and datasets can be combined.

[2] We compared 25 manual UW measurements of the coral reef with 25 digital measurements of the scaled point cloud model and calculated deviations at each measuring point. Both the minimum and the maximum value represents, respectively, the smallest and largest deviation over all 25 measuring points.

Alignment rates were similar for both models: 603 of 618 (97,6 %) and 619 of 642 (96,4 %) still images and 912 of the 912 (100 %) extracted video frame images were aligned (Table 2).

3.2 Sources of error in UW photogrammetry from stills and video data

Following the exact protocol as in VSW19, the same error sources affect both 3-D scan methods. In short, the potential source of error in our underwater photo- and videogrammetry experiments is using not calibrated lenses for underwater refraction. It is challenging to determine the refractive index for seawater as water temperature, salinity and wavelength were changing parameters during our experimental [JKK16]. In the experiments, this effect was ignored. Therefore, deviations in both compared point cloud models from UW photogrammetry include refraction errors and errors from uncalibrated lenses. Calibration and refraction error multiply as the area covered grows. In the experiments datasets of the natural reef captured at different distances to test on how this effect evolves was not included. In future proposals, the experiments would benefit from testing methods in a wider area. The underwater camera system used was confined in an underwater housing with one viewing the scene through a macro port, a flat piece of glass. Light rays entering the camera housing are refracted due to different medium densities of water, glass and air. This causes linear rays of light to bend and the commonly used pinhole camera model to become invalid. When using the pinhole camera model without explicitly modeling refraction in SfM methods, a systematic model error occurs [JK13]. Photogrammetry models are susceptible to alignment errors causing scaling errors and ghosting, a phenomenon when two image data sets are combined and reconstructed more than once at a different location. Even in well aligned high precision models an error of 3 cm is possible depending on how accurate the scaling has been performed in photogrammetry software. A high amount of moving objects such as fish, soft corals, shadows from sun or light sources projected onto the sand and backscatter, strobe reflections from moving particles in water all cause image noise to appear in the images and can cause misalignments of collected data. Visibility is the key parameter for good alignments in both, photo- and videogrammetry. Both datasets, DS1 and DS2, were taken with a visibility larger than 30 meters with more than 96 % of the collected images able to be aligned.

4 Conclusions

In times of climate change and ecological crisis, this workflow offers a unique approach to UW survey coral reefs at close range using UW photo- and videogrammetry to reconstruct high precision 3-D point cloud models of corals and coral reefs. Aiding perception and understanding of the living underwater environment as 3-D reconstructed models visualized in high detail and creating accurate 3-D surface and textures configurations of the scanned natural reef. Respective practical, technical, environmental criteria and parameters for high-resolution 3-D reconstruction and comparisons from resulting 3-D models from photo- and videogrammetry of the same coral reef are discussed. Both methods result in 3-D point cloud models of different precision and detail and require different amounts of time and resources. Therefore, UW photogrammetry could be implemented for detailed studies of high precision surveys of individual corals whereas UW videogrammetry could be used for faster scans of larger survey areas. Both methods can be applied to study details in growth processes of corals or e.g. to monitor different stages of coral bleaching. Point cloud models represent the physical form of underwater objects and can be used as a tool for spatial analysis, Virtual Reality models or WebGL models in online 3-D content libraries such as SketchFab [Sk19]. Underwater point cloud models can be converted into digital surface models for structural analysis, hydrodynamic modelling, or digital fabrication such as 3-D printing to represent scanned reef areas as physical model. Furthermore, at high visibility both methods can be exploited in other areas of marine and environmental modelling for static objects such as underwater inspection and monitoring of oil and gas pipelines.

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