High-Resolution Underwater 3-D Monitoring Methods to Reconstruct Artificial Coral Reefs in the Bali Sea: A Case Study of an Artificial Reef Prototype in Gili Trawangan

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Abstract: This paper discusses a novel approach for artificial coral reefs. In our case study – pursued at the shoreline of Gili Trawangan (Indonesia) – we present new methods and techniques for their design and fabrication, and, ultimately, to enable regrowth of damaged coral reefs. Of particular importance is the use of underwater laser scanning and underwater photogrammetry for surveying marine environments. When calibrated and used correctly, these visual sensors are well-suited for automated detection, quantification, mapping, and monitoring applications, particularly for high-accuracy 3-D models or change detection (JORDT 2016). In this context, the intricate structural complexity of a reef formation, especially of scleractinian corals, challenges capturing high-accuracy 3-D models at close-range. In our contribution, we present a) the overall approach and the chosen case study, b) the specific workflow to survey marine environments with millimeter precision, and c) a comparison between different 3-D scan methods applied in this context, including LiDAR scanning (M210UW Newton Labs underwater laser scanner), and high-resolution underwater photogrammetry (Sony Cyber-shot RX100 II, Canon EOS 5Ds). Against this background, we discuss the applicability of both methods and their viability for voxel models from high-resolution computed tomography (CT) scans of an extracted sample of Prototype 1.

Keywords: Artificial coral reefs, underwater photogrammetry, underwater laser scanning, CT scan, 3-D modelling

1 Introduction

1.1 Objectives

In times of climate change and ecological crisis, ecological restoration of depleted ecosystems has become an essential topic in the field of landscape architecture. Landscape architects propose design interventions, investigate socio-economic, geo-political and urban-territorial implications on destroyed systems and establish accurate methods to precisely evaluate and monitor results and progresses over time. Coral Reefs in the Bali Sea are complex structures that prevent beaches from erosion, serve as habitat for sea life and are a major resource for the local fishing industry and tourism. Currently, however, they are threatened and partly destroyed by dynamite fishing, ocean acidification due to elevated levels of CO2, in turn, caused by pollution, and rising sea temperatures due to global warming. We propose an architectural design framework for semi-artificial reef systems that could help to repair damaged structures and to initiate new reefs. Reefs and corals are geometrically complex structures as plants and trees and form an interesting case study for close range digital 3-D modelling for landscape models (VOGLER 2018). Our high precision approach for digital models of artificial reefs in the Bali Sea can be applied to landscape models.

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In our case study – Artificial Reef Prototype 1 (ARP 1) – we compare two underwater 3-D scan methods (underwater laser scanning and underwater photogrammetry) to explore and validate their viability for 3-D point cloud generation of millimeter and submillimeter precision in the context of complex marine artificial reef systems. Through our experiments at Dive4Life Center in Siegburg, Germany (see Section 1.3) we initially tested the main technical constraints of both methods, as well as the hardware system required to enable high resolution (high-res) 3-D scans of ARP 1 in the specific context of Indonesia (see Section 1.2). During the experiments, we encountered major challenges in UW photogrammetry which affected data collection, data processing, and the data quality of the final 3-D point cloud model. More importantly, point cloud models from UW 3-D scanning only describe the outer surface of the ARP 1, whereas the interior structure of ARP 1 remained unknown. In the second part of the paper, we investigate if computerized tomography (CT) scans could augment 3-D point cloud models from underwater laser scanning or photogrammetry in artificial reef monitoring.

Methods for capturing precise 3-D models from close-range underwater surveys of coral reefs are currently under investigation in a number of different disciplines such as geology, archaeology, and marine biology. The Hawaii Institute of Marine Science used a 2G Robotics ULS 100 underwater LiDAR laser scanner (similar to the LiDAR system used by our team) for the close-range, high precision surveying of corals. 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 map a 305 m^2 coral reef near Reunion Island. They collected 1625 images for 3-D reconstruction with Pix4D software. Their goal was to identify bleached areas of the reef through a digital 3-D model (PIX4D 2016). Their reconstructed 3-D models reached an accuracy of centimetric resolution. The Hydrous, a U.S. based non-profit organization that creates "open access oceans" for people to engage with marine environments, have used close-range underwater photogrammetry to collect image data for 3-D reconstruction of natural coral reefs around the world since 2014. 3-D polygonal mesh models and textures of different coral topologies are available for download as Open Access Models on SketchFab, an online 3-D content library. These models can be repurposed as Virtual Reality (VR) models for video game design or 3-D modelling. These models have centimetric precision. In our research we propose a unique underwater workflow for both high accuracy 3-D scan methods (UW laser scanning and UW photogrammetry), techniques to capture complex objects as underwater data for high precision 3-D landscape models of high complexity, present challenges and potentials for underwater photogrammetry, and we discuss further possibilities to combine point cloud models with voxel models. Our high precision approach is novel for the monitoring of Biorock© based artificial reefs.

1.2 Case Study Object ARP 1 and ARP 1-Setup

ARP 1 is a digitally designed and fabricated artificial coral reef in the Bali Sea. The reef was launched in November 2012 at a depth of approximately 7 meters, about 60 meters off the shoreline of Gili Trawangan island in Indonesia (VOGLER 2018). The reef is 110 cm long, 90 cm wide, and at its highest point, 60 cm high. Artificial reefs in the Bali Sea are artificially produced underwater structures to foster regrowth of premorse parts of corals to help to repair local damaged reefs and to initiate new reef environments. To build such artificial reefs, multiple methods and materials were established. Prototype 1, for example, is based on the Biorock-technology developed in the 1970s by the German architect Wolf Hilbertz. Biorock reefs are made out of electrically conductive steel frames, often made from steel construction rebar or metal wire mesh (HILBERTZ 1996). In Hilbertz' technology, these are submerged and attached to the sea bottom. An electrolytic reaction precipitates mineral from seawater to accumulate calcium carbonate around the steel frames on which corals start settling (HILBERTZ 1979). Over time Biorock-reefs serve as habitat for marine life – both as a resource for the local fishing and diving industry and as a coastal protection device (GOREAU 2017). Following Hilbertz' initial approach, the design of ARP 1 (Fig. 1) is inspired by the Lindenmayer system fractals (L-Systems) to enhance the electrochemical process, and to mimic the geometry of patterns of tree growth, which can be found in several species of stone coral (ROZENBERG et al. 1980). It is composed of 100 identical, laser-cut sheet metal elements of 1.5 mm thickness, manually joined through push-fit connections. We assembled and installed it underwater during the 8th Biorock Restoration Workshop in November 2012. During our field research (ARP 1-Setup), we recorded an average growth of 25 mm of calcium carbonate layer around the metal pieces as a result of mineral accretion during the past five years. Corals grow on top and ARP 1 serves as artificial habitat for fish and other aquatic life.

Fig. 1: ARP 1 launch and growth throughout the past five years (2012-2017)

1.3 Preliminary Tests

We conducted a preliminary test of ARP 1 in the Dive4Life Center in Siegburg, Germany. The condition of the seven-meter-deep dive pool filled with fresh water was excellent, with visibility of more than 30 meters. ARP 1 was tested as a smaller version consisting of nine joined metal pieces, painted with a temporary waterproof matte paint. The matte color significantly improved the scanning results as the laser and the reflex camera would not return good results if reflective metal pieces were used. Finally, a plastic coral was attached using zip ties.

Fig. 2: Top row from left: painting of individual elements of test ARP 1; Preliminary tests at Dive4Life Center in Siegburg, Germany

1.4 Measuring Components of ARP 1-Setup

In this section, we briefly introduce three underwater 3-D surveying technologies to capturing high-accuracy 3-D models of ARP 1 at close-range in our ARP 1-Setup: underwater laser scanning (UW laser scanning), underwater photogrammetry (UW photogrammetry) and CT scanning. The absolute and relative precision of the tested measuring technique is of particular concern.

1) UW laser scanning is based on subsea LiDAR laser technology (Light Detection and Ranging), representing an established surveying method that measures the distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor.[1] Differences in laser return times and wavelengths can then be used to make digital 3-D models of the target (Lefsky 2002). Underwater Laser Scanning exceeds traditional underwater measurements by capturing as built point cloud data with submillimeter accuracy.

2) Photogrammetry multiview 3-D reconstruction, also known as Structure-From-Motion (SfM), is a technique for constructing three-dimensional structures from two-dimensional imagery. We used it during our field studies in Gili Trawangan to retrieve information of high-resolution underwater images to recover the exact three-dimensional position and color of surface points of ARP 1 (Drap 2012). Although photogrammetry in underwater environments is significantly more constrained than in aerial or terrestrial uses, it provides a robust and efficient measuring technique for environments with limited accessibility (Telem 2010). Through recent advances in camera technology and digital image processing software, the ability to use underwater photogrammetry for high-resolution 3-D reconstructions for underwater survey purposes has been greatly improved. Water is 800 times denser than air and therefore attenuates light much faster. Long wavelength light such as red nearly disappears at around five-meter water depth, followed by orange at approx. ten meter and yellow at approx. twenty meters. The loss of color increases not only vertically through the water column, but also horizontally. As

1 Newtown Labs, the manufacturer of M210 UWL, keeps detailed specifications about built- in hardware components confidential.

a consequence, objects beyond that distance appear colorless and indistinct (GIBB 2017). This issue can be solved combining two techniques: The first approach is to position the camera as close to the subject as possible to minimize horizontal loss of colour; the second technique is to use an artificial light source such as strobes or video lights. A high aperture number for maximum depth of field equates to less light coming into the lens. In that case, this deficit has to be compensated by higher ISO numbers, strobes and/or lowering the distance between camera and object (e. g. using aperture 22 -> distance to object 0.25 m). Still, ISO should be set to the lowest value possible, otherwise high ISO values will introduce additional noise to images (AGISOFT 2018).

3) CT scanning is a method where many X-ray measurements are taken from different angles to produce cross-sectional (tomographic) images to further generate a three-dimensional volume of the inside of the object (HERMAN 2009). High-resolution CT widely expands the spectrum of detectable internal micro-structures. The nanotom CT system allows the analysis of samples with the exceptional voxel-resolution of less than 0.5 microns per volume pixel (voxel). Thus, internal detail related to a variation in material, density or porosity can be visualized and precisely measured. Therefore, it is particularly suitable for Nano CT-examinations of material samples of any type like synthetic materials, ceramics, composite materials, mineral, and organic samples. By means of volume visualization software, the three-dimensional structure of the reconstructed volume can be easily analyzed for pores, cracks, and material density and distribution with the highest magnification and image quality available (BROCKDORF 2007).

2 3-D Underwater Survey Methods and Results

After a general introduction of three survey technologies used, this section focuses on the implementation and validation of underwater 3-D scan methods. During our preliminary tests (see Section 1.3) we collected and compared highly accurate 3-D scan data sets from scans with a M210UW Newton Labs Underwater Laser Scanner and two underwater photogrammetry scans from two still camera systems: Sony Cyper-shot RX100 II and Canon EOS 5Ds. During our field survey in Indonesia (see Section 1.2) we focused on a complete scan of ARP 1 using underwater photogrammetry with the Canon EOS 5Ds still camera system.

2.1 UW Laser Scanning with M210UW Newton Labs Underwater Laser Scanner

Newton, the manufacturer of M210UW is the largest manufacturer and supplier of underwater laser scanners. M210UW is their specific model for extremely high-resolution scans within one-meter range. Currently, there are only a few alternative hardware providers to capture 3-D underwater high accuracy survey data that operate with subsea LiDAR such as UW laser scanner from 2G Robotics, Sonardyne or Kraken Robotics. M210UW accuracy is related to the field of view, distance from the object to be measured, and can vary by the parameters of the object. Accuracy when used with a fixed laser line and an inertial measurement unit (IMU) for position data, depends on IMU update rate and speed of travel (NEWTON LABS 2015). M210UW reaches a total scan range of 150 mm to 900 mm and was calibrated for water during our experiment. The scanner was attached to a rectangular steel framework of 1.2 × 1.2 meters. The scanner's head could be rotated 90 and 180 degrees to enable scans in x and y direction. The ARP 1 test model was placed underneath the framework on the ground. Three metal rulers, longer than the test model, were positioned alongside in the x and y direction.

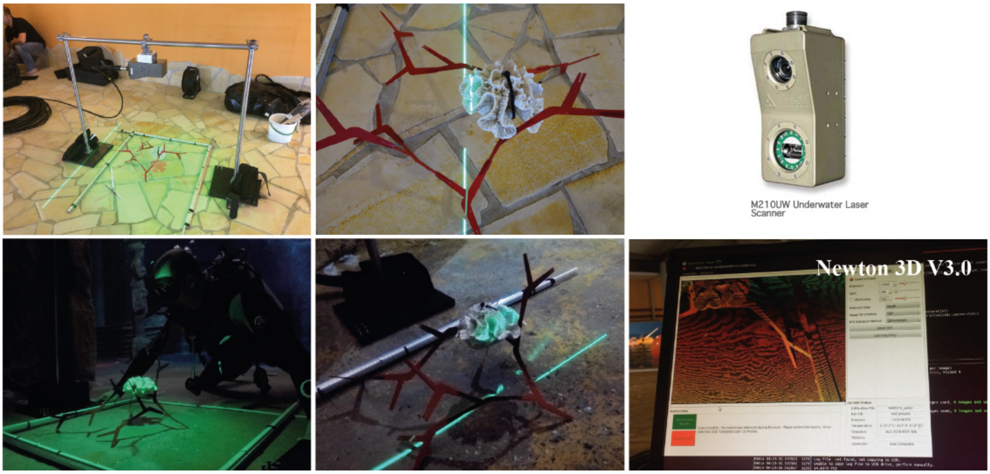

Fig. 3: Top row from left: laser scan test setup at Dive4Life Center in Siegburg, Germany; M210UW Underwater Laser Scanner; Underwater test setup; Linux workstation displays in Newton 3D V3.0 software scan result

The M210UW system operates with Newton 3D V3.0 software installed on a Linux workstation at the surface. An underwater cable connects the scanner at the bottom of the dive pool with the workstation. Before the scan, the M210UW integrated underwater camera displayed the target scanning area in the Newton 3D V3.0 software. For each scan, we repositioned the laser scanner orthogonally by 25 cm respectively in x and y direction. We captured the entire test model with 22 individual scans of 610,000 points each. Individual scans were aligned with point pairs picking (CLOUDCOMPARE 2017) in CloudCompare V2.10.1, a 3-D point cloud processing software, resulting in a 3-D point cloud model of submillimeter precision.[2] In total, these scans took about seven hours to conduct.

2.2 UW Photogrammetry

During our preliminary tests (see Section 1.3) we tested and evaluated two different still underwater camera systems: Sony Cyper-shot RX100 II and Canon EOS 5Ds R. We wanted to compare a compact camera system with a professional reflex camera system. The Canon EOS 5Ds R is a camera with one of the best image sensors and highest output resolution on the current market.

[2] Hardware manufacturer Newtown Labs of M210UW specifies an approximate CAD model accuracy within a range of 0.01 mm – 0.15 mm depending on the distance to the object. Specific parameters to reach these values in an experimental setup are not determined by the manufacturer.

Table 1: Main characteristics of two still camera systems and one moving camera system tested

	Sony Cyper-shot RX100 II	Canon EOS 5Ds R
Manufacture	Sony	Canon
Image sensor	20.2 MP, 13.20 mm × 8.80 mm	50.6 MP, 36.0 mm × 24.0 mm
Sensor type	CMOS	CMOS
Maximum output resolution	5472 × 3648	8688 × 5792
Shutter speed	1/2000 s – 30 s	1/8000 s – 30 s
ISO rating	100 – 12,800	100 – 6,400
Optical focal length (35 mm equivalent)	28 mm – 100 mm*	23 mm – 50 mm **
lens aperture	22*	32**
Closest focusing distance	5 cm*	23 cm**
Auto-focus	TTL-CT	TTL-CT-SIR, one Shot, Al Focus, Al Servo
Manual focus	Yes	Yes
Still image type	JPEG, RAW	JPEG, RAW
Light Source	One video light	Two SEACAM strobes (SF150D)
Underwater battery life time	70 min	70 min, strobes SF150D: 25 % approx. 800 still images

* ZEISS® Vario-Sonnar® T* Lens
** Canon EF 50 mm f/2.5 Compact Macro

We collected the same still image data using Sony Cyper-shot RX100 II and Canon EOS 5Ds R. With each camera system we shot one complete photogrammetry set, defined by a number of still images taken at a distance of 30 cm between camera and object following a so-called "lawn-mover" photogrammetry pattern with 60 % of side and 80 % of forwarding overlap (AGISOFT 2018). Camera settings such as aperture value, ISO number and image resolution were kept constant, respective to each camera system. Each data set was taken in a separate dive. PhotoScan Pro Version 1.4.4 (Agisoft) image processing software was used to reconstruct 3-D point cloud models.

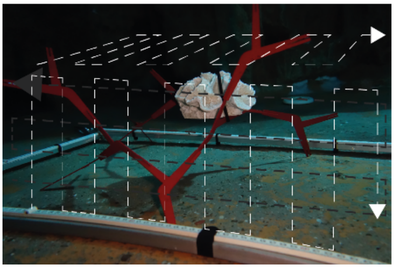

Fig. 4:
Lawn-mover pattern for still images for top, left, right and front faces of the test Prototype 1.
The bottom side of ARP1 test model could not be captured.

Our resulting point cloud model reconstructed from high-res still images (5472 × 3648 pixel) from Sony Cyper-shot RX100 II has 16,901,081 points. 113 out of 185 images were aligned in PhotsScan Pro Version 1.4.4. The reconstructed model is complete, except missing parts on the lower side. After taking ten test measurements of the physical model and the reconstruction respectively, we calculated an average deviation of ±1.8 mm. Shadows from the video light are visible in the 3-D model. Resulting point cloud model of high-res stills (8688 × 5792 pixels) from the Canon EOS 5DS R reflex camera has 16,399,865 points. 89 of 190 images were aligned. The average deviation of precision is ±1.1 mm. The reconstructed model displays high detail and does not show hard shadows. From our two tests, the deviation between 3-D reconstructed models of both still camera system is ±0.7 mm.

Fig. 5: Both camera systems enabled reconstructions of complete 3-D point clouds of millimeter accuracy

During ARP1-Setup (see Section 1.2), we collected two complete photogrammetry data sets for ARP1 using a Canon EOS 5DS R reflex camera together with a Canon 50 mm 2.5 Macro Lens inside of a SEACAM Underwater Housing 5DMKIII and two SEACAM strobes (SF150D). In thirteen dives we captured still images for both data sets. Camera settings, especially ISO values had to be redefined and adjusted for each dive.

Fig. 6: ARP1-Setup (see Section 1.2). Taking photographs following lawn-mower pattern of one of the faces of ARP1, Portable plastic rulers with led attached were placed as reference next to ARP 1; about 200 manual measurements of ARP 1 were taken and documented.

In total, we produced 4058 still images at a resolution of 8688 × 5792 pixels. Alignment rates increased in PhotoScan Pro Version 1.4.2 from 33 % (all stills) to 98 % (e. g. 889/ 902 for Dive 10) when we processed still images data separately for each dive. We processed thirteen different point cloud models and merged them in Cloud Compare V2.10.1. Our results show reconstructed models of high complexity, completeness, and of fine-scale detail of millimeter precision (Figure 9). We calculated deviations between our manual measurements and the final 3-D point cloud of a range between 2 to 7 mm. Our final point cloud model is incomplete on the bottom side of ARP 1 and lacks in detail in areas where soft corals grow.

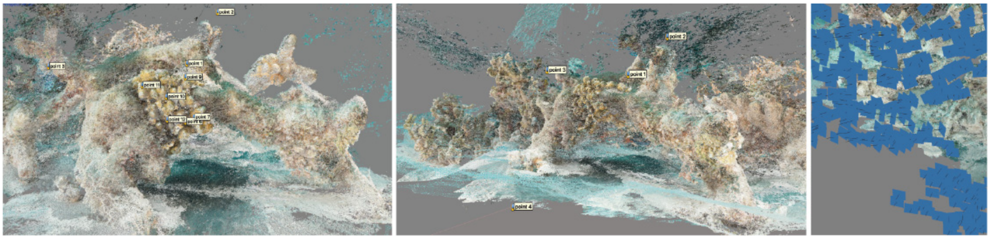

Fig. 7: 3-D reconstruction point cloud model of ARP 1. We used all 4058 still images collected at low resolution. Only 1368 images (300 KB) out 4058 of were aligned.

Fig. 8: Top row from left: Partial 3-D reconstructed point cloud models of ARP 1 of still images collected during one dive. They were processed at maximum resolution (709 images aligned out 795 of 8688 × 5792 pixels). Bottom row from left: Details of high accurate point cloud model of ARP 1.

2.4 Grey Scale Analysis of Extracted ARP 1 Sample

In this section, we introduce our results from a nanotom CT scan of an extracted sample of ARP 1 (Figure 7). Through grey scale analysis, we can further understand the interior composition of ARP 1 at sub-millimeter resolution. We used CT Scanner Nanotom M "research edition" with nanoCT® technology. The system is specially designed for scientific and industrial CT applications (micro-CT and nano-CT) and 3D metrology. It achieves unique 3-D and contrast resolution ensuring fast and reliable CT results.

Fig. 9: From left: Extraction of sample; CT Scanner Nanotom M "research edition" at F.A. Finger-Institute for Materials Science of the Bauhaus-University Weimar

We CT scanned ARP 1 sample at a resolution of 0.13336 m

mm. With CT-data processing software Volume Graphics VGStudioMAX a voxel model was reconstructed from the collected image data. The software allows one to navigate through the internal structure of ARP 1. Grey scale analysis displays that there are areas of higher and lower density in the 3-D model. Lighter grey values represent materials of high density while darker ones represent materials of less density. Looking at the longitudinal- and cross-sections of the 3-D voxel model, the results clearly show that outer calcium carbonate layers are of a much higher density than the layers around the metal piece.

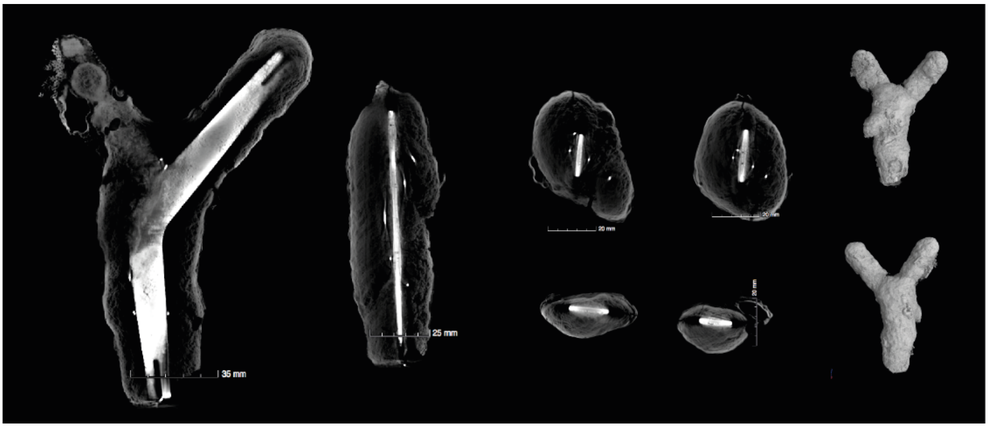

Fig. 10: Grey scale analysis displays that there are areas of higher and lower density in the 3-D model. Voxel model displayed in Volume Graphics VGStudioMAX shows growth of calcium carbonate layer and condition of metal piece inside of the artificial coral reef.

3 Discussion

3.1 Comparison UW Laser Scanning Versus UW Photogrammetry

The main criteria in the comparison of both methods is precision and level of detail in the resulting point cloud model. The different types of equipment used only to have an exemplary function. The relationship between the context and use case is critical which will be explained in more detail section 3.2.

Table 2: Comparison of three hardware systems used for UW laser scanning and UW photogrammetry

	M210UW Newton Labs	**Sony Cyper-shot RX100 II**	**Canon EOS 5Ds R**
Setup type	Preliminary test	Preliminary test	Preliminary test / ARP1 Indonesia
Target object	Test model ARP 1	Test model ARP 1	Test model ARP1 / ARP 1 Indonesia
Calibration	Water	Air	Air / Air
Number of dives	6 dives	1 dive	1 dive / 13 dives
Collected data	22 individual scans as point cloud	One complete scan: 185 still images (5472 × 3648)	One complete scan: 190 still images (8688 × 5792) / Two complete scans: 4058 still images (8688 × 5792)
Point cloud models	22 models	One model	One model / 13 models
Number of points	610,000 points each scan	16,901,081 points	16,399,865 points / e. g Dive 12: 297,185,130 points
Deviation	±0.6 mm	±1.8 mm	±1.1 mm /±2 to 7 mm
Time	7 hours	45 min	45 min / 17 hours
Handling	30 kg + 1 diver, 1 assistant 1 boat or platform for workstation	0.8 kg 1 diver	12 kg 1 diver
Costs	high cost for equipment, logistics and transportation	Low-cost, only equipment	Low-cost, only equipment

M210UW Newton Labs UW laser scanner calibrated for water returned 22 exact point cloud models of test ARP 1 with a precision of 0.4-0.8mm. In this particular case, UW laser-scanning returned a five times more accurate result than the other 3-D models, built upon UW photogrammetry. Above all, the CT-scanned 3-D model is complete and displays the coral in great detail. However, a team of minimum two people was necessary during the entire experiment: one diver who supervises and moves the scanner underwater and another assistant on land to operate the workstation and software. Communication between both team members presents an additional challenge as direct visual or audio communication is disabled.[3] The deviation between 3-D point cloud models from underwater laser scan data with M210UW Newton Labs UW laser scanner and UW photogrammetry with Sony Cyper-shot RX100 II can be optimized at a minimum of ±1.7 mm. We compared both point clouds with Cloud-to-Cloud Distance computation (CLOUDCOMPARE 2017) in CloudCompare V2.10.1. In comparison, UW photogrammetry equipment is financially affordable, transportable and can be handled by only one diver. No additional hardware on land needs to be connected to underwater instruments. Total weight of equipment was about 12 kg instead of 30 kg for the underwater laser scan equipment. The UW laser scan measurement procedure with M210UW Newton Labs UW laser scanner for test model ARP 1 (7 hours) took 9 times longer than taking UW photogrammetry measurements of the same model (45 min). Both methods, UW Photogrammetry and UW Laser Scanning, have the potential to monitor complex underwater landscape models at high precision and are applicable. In a commercial environment, greater financial resources are available.

3.2 Additional Challenges

Major issues occurred that challenged UW photogrammetry in the field. A high number of moving objects such as fish, soft corals, thin hairs of fire coral growing on top of the structure provoked misalignments of overlapping images. Shadows caused by sunlight or artificial light sources such as strobes and video light result in hard shadows projected to the sand. Backscatter, a light from a strobe reflecting back from moving particles in water causing image noise to appear in the photo. Stronger currents promote the quantity of moving particles and affect visibility, the key parameter for good alignments in underwater photogrammetry. In datasets taken with visibility larger than 20 meters, more than 95% of images could be aligned. In the field, we struggled with a range of visibility from eight to 35 meter. Datasets taken at visibility lower than 20 meter showed lower alignment rates of less than 50%. For that reason, we had to align datasets taken during each dive separately, meaning that each dive corresponds to one 3-D reconstruction. The number of dives affects the quality of the overall 3-D model. The higher the number of partial models, the higher the error rate in the final 3-D model. A potential source of error in our underwater photogrammetry experiments is using not calibrated lenses for underwater refraction. It is challenging to determine a refractive index for seawater as water temperature, salinity and wavelength were changing parameters during our experimental (JORDT 2016). In our experiments, we ignored this effect. Therefore, deviations in both compared point cloud models from UW laser scanning and UW photogrammetry include refraction errors and errors from not calibrated lenses. Calibration and refraction error multiply as the area covered grows. In our experiments, we did not include photogrammetry datasets of ARP 1 captured at different distances to test on how this effect evolves. Therefore, we propose to test this method in a wider area. Both underwater camera systems used were confined in an underwater housing, 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 usually linear rays of light to bend and the commonly used pinhole camera model to be invalid. When using the pinhole camera model without explicitly modeling refraction in SfM methods, a systematic model error occurs (JORDT-SEDLAZECK 2013). Photogrammetry models are susceptible to alignment errors causing scaling errors and ghosting, a phenomenon when two image data sets are

[3] Wireless diver communication solutions exist but were not used during our experiments.

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.

4 Conclusion and Outlook

This paper offers a comprehensive new approach to computational design and landscape architecture research. While state-of-the-art techniques enabled high-quality digital reconstruction of large-scale structures, e. g., urban and landscape environments, we focused on sparse representations and dense reconstruction of smaller landscape objects of high complexity to study growth and surface configurations at millimeter precision. Our research presents several techniques for close-range three-dimensional underwater survey processes of artificially designed and constructed underwater landscapes and discusses respective practical, technical and environmental criteria and parameters. The results are transferable to natural underwater landscapes, where coral reefs form excellent study objects for the exploration of high-resolution 3-D scanning and modelling methods. Coral reefs – both artificial and natural – are geometrically and structurally complex and present many challenges regarding 3-D scanning and modelling their intricate surface configurations, and growth processes in particular. To address these challenges, we have a) developed a specific experimental setup including a computationally designed artificially constructed coral reef prototype, b) defined key parameters, and c) implemented different state-of-the-art techniques to scan and model coral reefs in real-world underwater configurations. Here, manifold high-resolution 3-D point cloud representations enabled to visualize and measure scanned coral reef structures of millimeter and submillimeter precision, and therefore to study growth processes, surface and material configurations. Ultimately, such underwater point cloud models could be converted into digital surface models, for example, using algorithms for polygonal meshing and be used for further computational design studies, growth and structural analysis, hydrodynamic modelling, and digital fabrication and repair of reefs using calcium carbonate-based powder. Thus, the presented approach promotes information penetration across the whole process, from the design and fabrication of artificial coral reef structures to the scanning of real-world underwater growth, opening up new ways of thinking about computational design and three-dimensional scanning and modelling. On that scope, it is a vision of process, not just a product. As identified in this paper, the amount of available research on this topic is not abundant, and no comprehensive experiments have been conducted in the field of computational design and landscape architecture. And yet this approach is captivating: underwater survey processes not only creates a new vision for computational design in landscape architecture, but also emphasizes new possibilities for the perception and understanding of it, and thus of our living environment.

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