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Underwater photogrammetry

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Abstract. The paper presents the nature and principles of underwater photogrammetry, the features of the environment, and the means and methods for data capture and processing. It discusses the current state of underwater photogrammetry and presents an overview of its applications. The aim is to introduce divers, researchers, and other specialists to the possibilities offered by underwater photogrammetry. The paper presents a comprehensive overview of the methodology from data acquisition to the generation of a three-dimensional digital model. The paper can also help recreational divers to broaden their professional interests and subsequently retrain and start providing data for use by geologists, biologists, engineers, ecologists, and other specialists. Similarly, it can also help professional divers and diving instructors to expand their knowledge so that they can carry out activities related to tracing and monitoring underwater infrastructure. Finally, diving associations can benefit from this paper if they use it to promoting underwater photogrammetry and its applications.

1. Introduction

The availability of high-quality data, such as textured digital models and orthophotos, acquired in underwater environments enables specialists from different fields to extract information about heterogeneous objects and analyse processes in the underwater world. Over time, close-range photogrammetry has evolved and become increasingly established as a method for capturing in the underwater environment [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Although acoustic sensors are widely used for surveying in underwater environments [11, 12], photogrammetric methods are preferred since they provide images with high spatial and radiometric resolution resulting from the close range capturing. This methodology does not allow only detailed mapping [9], but also provides high-accuracy three-dimensional models (within 5 cm) for archaeology [7], for tracking coral reef growth (within 10 mm per year) [13], etc.

Photogrammetric capturing is not time-consuming and is performed remotely. The large amount of data raises the issue of the methods of data acquisition and the efficiency of photogrammetric processing. The use of the structure-from-motion (SfM) method [14] enables the processing of images acquired at different angles and distances to the object under study, thus providing a relatively simplified methodology compared to other methods. Over the years, it has been established as a flexible, accurate, and affordable method applied to underwater seabed mapping [15]. Another important advantage associated with the use of underwater photogrammetry lies in the variety of products it provides (3D measurements on the object, 3D reconstruction, orthophotography, and vector restitution) [1].

All of these advantages determine the application directions of underwater photogrammetry. Part of those is bound to the **off- and on-shore industry** for the inspection of pipelines, platforms, and subsea equipment, support for repair and maintenance activities, and for underwater construction [16, 17, 18]. The documentation, study, and promotion of **archaeological sites and cultural heritage** [10, 19, 7, 6, 20] forms another major area of application, with particular interest in the study of shipwrecks [3, 4, 21]. Underwater photogrammetry is a good tool that is also used in **marine biology, underwater conservation, and ecology**. Over time, its application has increased establishing it as an efficient and accurate method for specialists to solve various problems in these fields [22, 23, 24, 13, 25, 26, 9, 27, 28]. In the area of **forensics**, photogrammetry is also finding its place although, due to the nature of the work, little material has been publicly reported [29, 30]

Sometimes, due to the local conditions available and the specifics of the task, various complementary remote sensing techniques are required in order to perform underwater mapping [31, 32, 33, 34]. But whether a single method or a combination of several methods will be used for underwater and surface environment capturing, its influence must be taken into account. It is also essential for the selection of appropriate equipment.

2. Factors of the underwater medium

Underwater capturing differs from shooting on land, as the refraction rates of light underwater are different from those in the air. This is due to the different densities of the media (air-water), which determines the different speeds of light propagation.

The difficulties in underwater photogrammetric capturing result from inconsistent lighting conditions, the change of refractive index, and colour loss due to the limited penetration distance of certain wavelengths. Color loss is due to the limited penetration distance of certain wavelengths. For example, red light is absorbed within the first few meters of the water surface. After 40 m, only blue light is visible. It should be noted that the range also depends on whether the waters are oceanic or coastal. The penetration range of blue light is greater in oceanic waters. Water transparency also plays an important role. The clearer the water, the deeper the light can reach before being absorbed or scattered. This is precisely why blue light can reach depths of over hundreds of meters in crystal clear waters. Generally, with the increase in depth, the colours disappear - only 1% of visible light reaches 100 m and less than 0.1% penetrates to up to 200 m [17]. Depending on which waves of the electromagnetic spectrum fall on the object captured, the colors underwater change. With the increase in depth, they may disappear - at 40 meters, all objects appear grey-blue. However, at such depth, colours can be restored but only if the objects are illuminated with an artificial light source [35]. It should therefore be borne in mind that with capturing at great depths, additional artificial light sources are needed. Usually, these are protected in the same kind of housing as cameras. One more fact should be taken into account: they, too, are subject to the effects of refraction [36].

Illuminance depends on reflection and scattering in a water environment. Some of the sun's rays are reflected from the surface. The degree of reflection depends on the angle of incidence. The least light is reflected from the water surface when the sun is at its highest. Then the angle of incidence is the smallest [35]. It should be noted that due to the refraction of light rays, objects under the water are seen closer and larger than they really are. In addition, the specific constraints of the underwater environment, like turbidity of the water and the presence of small suspended particles (sand, phytoplankton, and others), can dramatically affect underwater visibility. When light strikes the particles in the water, it is reflected in all directions (scattering) and this can result in a blurred image. By improving visibility, the process of creating photogrammetric models is facilitated. The lack of light is an obstruction to obtaining a sharp image of the object, which is critical for creating high-quality models. In turbidity water, artificial lighting (constant lighting or strobes) tends to generate backscatter, causing overexposure and focusing issues. A more effective way is to reduce the camera distance to the object, as was done in the study implemented in the Bulgarian Black Sea [5]. Light intensity varies due to light attenuation, weather conditions, site topography and turbidity [37].

Scuba divers must be familiar with the principles of photogrammetry, the capture methods, the equipment used, and the processing methods in order to adapt underwater capturing to local visibility conditions.

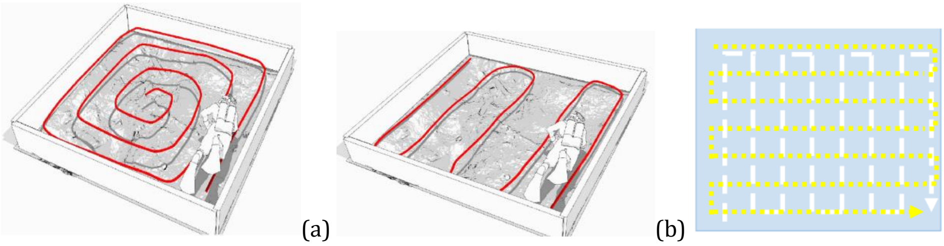
3. Method of capturing and Equipment used

3.1. Method of capturing

To obtain a geometrically accurate and complete three-dimensional model of an object, it is necessary to follow certain rules in the perspective capture. The images must be taken in different locations or positions in space, so that they cover the entire object observed. Work is typically performed with a set of images, with a percentage of overlap between them. Usually, area objects are captured when solving most of the underwater problems, which is why side overlap is added to front overlap. The recommended overlaps between images are within the range of 80 to 90% for the front overlap and from 60 to 80% for the side overlap. These values are adjusted according to the acquisition conditions, the 'texture' of the area, the precision required, etc. [15]. The image overlap is of high importance for vertical and horizontal accuracy of model. Key points are extracted from the overlapping sections in all images. Based on these, the point clouds are formed and, subsequently, the three-dimensional texture models. Therefore, the characteristics and quality of the image material (spatial resolution, presence of noise, blurring, etc.) are essential.

Spatial resolution is defined as the smallest discernible detail in an image. It is related to the capabilities of the sensor. A higher spatial resolution means the sensor can detect smaller objects or details in the image. Model detail and accuracy depend on ground simple distance (this is the distance between pixel centres measured on the ground or object). Ground Sampling Distance (GSD) defines the size of a single pixel in an image as measured on the ground. This value depends on the camera's focal length, the resolution of the camera sensor, and the camera's distance from the object. It is usually described in centimetres per pixel (cm/px). The smaller the value of ground simple distance is, the more detail in the model is displayed.

In addition to the features and quality of the captured images, the accuracy and completeness of the final result (the three-dimensional model) are influenced by the positions and orientation of the cameras relative to the object observed. These should be adjusted in such a manner that a continuous (complete) coverage of the imaged area or object be obtained. In practice, the following capture methods are mainly used: in a spiral trajectory, in the form of a stripe, or a grid (Fig.1).



(a) (b) (c)

Figure 1. Scheme of capture: along a spiral trajectory (a), in the form of a stripe (b) or a grid (c). Source: (a,b) Pacheco-Ruiz, 2018 [5] (c) Theague, 2017 [40].

It is good to know that specific application tasks exist (e.g. capturing objects that are situated under and above water) where tailored photogrammetric capture approaches have been developed [38]. Others are in use for archaeological purposes where aerial and underwater photography are combined [39].

Depending on the conditions of the underwater environment, the depth, the equipment, and the specific task, capturing can be performed by trained scuba divers or robots using one or more digital cameras, or by unmanned aerial vehicles (UAVs), autonomous vehicles (AUVs), or remotely operated vehicles (ROVs).

The awareness of the characteristics and capabilities of the instrumentation is essential in selecting the appropriate capture tool.

3.2. Equipment used

The purpose of the set of tools presented is to introduce divers, specialists in other areas, and amateurs with to the necessary equipment and its characteristics, as well as to guide them in their choice of capture tools.

Each underwater capturing kit includes a camera with a lens, an underwater box, and a flat or dome port. The underwater box (housing), is a case or housing that protects the camera from water. Dome port has a hemispherical glass or acrylic structure to provide a wide field of view for cameras[19]. See the link for further information about camera types https://lz1ccr.com/?p=46.

In addition to digital cameras, Remotely Operated Underwater Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) have become widely used in recent years.

3.2.1. Action cameras

Different types of camera have been produced that are applied in underwater capturing. Some of the most common are action cameras. These digital devices are compact in shape and are placed in a waterproof underwater box. The most popular models are presented (GoPro from Hero 3 to 12 black, DJI Osmo Action 4, Insta360 Ace Pro, etc.), which have been on the market the longest and are widely distributed around the world. The specification of each action camera indicates the depth at which it can be used with or without an underwater box. The Hero 5 Black is the first waterproof model of the GoPro cameras, up to 10 metres. The use an underwater waterproof box was mandatory for all previous models. It is recommended for all camera models. The original transparent boxes provide protection at a depth of up to 40 - 60 metres depending on the model. Boxes made of delrin or aluminum of other brands (Issota, Recsea, Easydive, IQsub, Anglerfish, etc.) are also available. They are for use at up to 100 - 300 metres, but their cost exceeds the price of the camera itself. The original boxes are sufficient for recreational diving and are also used by divers in scientific research. They are cheap to replace. Depth boxes are suitable for technical divers shooting between 50 - 120 metres deep. Another camera is the DJI OSMO Action 4, which is waterproof up to 18 metres of depth, has a color temperature sensor, and a fast battery charge of up to 80% in 18 min.

3.2.2. Compact cameras

Compact waterproof cameras (amphibians)

Representatives of this type of camera are some models from the Ricoh WG, Pentax WG, Olympus TG, etc. Unlike action cameras, these have a larger display, built-in flash, different shooting modes, such as macro, optical zoom, control buttons. They are waterproof up to a depth of 14 - 20 metres. Additional original underwater boxes are available that provide protection at up to 45 metres, as well as third-party ones providing protection at up to 100 metres. Various manufacturers offer extra lenses, dome ports, flashes, and video lighting.

Compact cameras

Underwater boxes are only produced for a limited number of the models of such cameras marketed. High-quality representatives of this class of cameras are the *Sony RX100*, *Canon Powershot G7 X*, etc. They have a 1-inch sensor, the different generations have improved focusing, better low-light performance, resolution, and frame rate. For most of them, there is a sufficient selection of underwater boxes from various manufacturers (Nauticam, Fantasea, Isotecnic, Ikelite, Kraken, etc.), made of different material, the most expensive being aluminum.

3.2.3. Mirrorless and DSLR cameras and interchangeable lenses

Mirrorless and DSLR cameras with a crop sensor and interchangeable lenses

Another type of cameras are mirrorless and DSLR cameras with a crop sensor and interchangeable lenses. The crop factor is an important feature when choosing the right lenses with the right field of view. It is not uniform with different manufacturers' models. For example: crop factor 2.0x (4/3) on Panasonic Lumix DC-G7, DC-G6, DC-G9 II, OM System OM-1 Mark II; crop factor 1.6x on Canon EOS R7, R5; crop factor 1.5x on Nikon D5600, D7500, Sony a6700, Fujifilm X-T50, etc. For Mirrorless and DSLR cameras, a wide variety of boxes by various manufacturers are also available (Ikelite, Nauticam, Aquatica, Isotecnic, Subal, etc.). They cover a maximum depth of from 60 to 100 metres. The more expensive models are again made of aluminum. There are a variety of flat and dome ports, according to the lens model. The cheaper ports are acrylic, the more expensive ones are glass, and the price varies according to size and quality. A budget camera kit can be assembled with a crop sensor, one lens, an underwater box for up to 60 meters, with an acrylic dome port, for the price of a nice full frame unit. If one chooses an aluminum underwater box with a large diameter glass dome port, the price doubles or triples.

Mirrorless and DSLR cameras with a full frame sensor and interchangeable lenses

A 35 mm frame is used as the sensor size reference for cameras. This is the so-called full frame sensor, with a crop factor of 1. Its size corresponds to 36 mm x 24 mm with a useful area of 864 mm^2. The diagonal of the sensor is 43.27 mm (calculated by the Pythagorean theorem); when this is divided by the diagonal of another sensor, its crop factor is obtained. The useful area of the sensors is similarly compared. For a 1.5x (380 mm^2) crop sensor, it is 2.27 times smaller; for a 2.0x (225 mm^2) sensor, it is 3.84 times smaller; for a 2.7x (116 mm^2) 1-inch sensor, it is 7.45 times smaller; and for a 1/1.9 sensor, 5.1x (34.04 mm^2) is 25.41 times smaller. Thus, different classes of cameras can be assessed and the choice of the right technique for your needs and budget be facilitated.

Full frame cameras are divided into two types: mirrorless and DSLR. Current representatives of mirrorless cameras are: Sony a7R V, IVa, IIIA, Nikon Z6 III, Z7 II, Z8, Panasonic Lumix DC-S5II, Canon EOS R8, R6 Mark II, etc. DSLR cameras are represented by: Nikon D850, D780, D750, D6, Canon EOS-1D X Mark III, and others.

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The same manufacturers of boxes and accessories can be listed as those of the cameras with crop sensors. A budget option may cost more than the camera; a variant with an aluminum box allowing it to be used at 100 meters, with a glass dome port, and abilities for accessories to be added, it will cost over two or three times the price of the camera.

3.2.4. Accessories

In addition to the basic toolkit, accessories, such as a handle, "arms", flashes, underwater video lighting, and a flat or dome port for the underwater box, are also used. See the link for further visual information about accessories https://lz1ccr.com/?p=41. The underwater box with the camera is mounted on the handle, along with "arms" holding flashes or video lighting, and additional accessories. The "arms" are different models, made from flexible sectional tubes to tubes and flat profiles with holes in them, ending with ball bolts clamped in lockable "joints", giving great freedom for adjustment. They are fitted with an adapter for mounting the lights. "Arms" with in-built buoyancy are also used. These are made of closed tubes of varying length and diameter, which help to easily achieve neutral buoyancy of the entire set. The flashes used are of great importance in underwater photography. A set of two quality flashes can exceed the price of the digital camera used (Seacam Seaflash 160 Digital, Isotta RED64, Refra Flash Prime, Ikelite SubStrobe DS230, etc.). For the success of underwater capturing, it is important to know certain characteristics of the flashes used, for example, how many pictures can be taken with one set of batteries, what the recharge interval of the flash is, whether it overheats with continuous use. If the batteries are built-in, it is necessary to know how long they take to charge in order to plan dives.

Underwater video lighting.

For good results, a set of two nice lights is needed, with a wide angle of illumination, adjustable light intensity, and long battery life. A budget option is about the same as the price of the camera (Keldan Video 4x 10K Lumen, 8XR 20K Lumen, Light & Motion Sola Video Pro 15000, Big Blue VL5800P, etc).

A flat or dome port for underwater housing.

Flat ports that are used underwater reduce the field of view by about 30% compared to those used on land. Because of this, the object appears closer; therefore, the focal length increases. Refraction has a greater impact and chromatic aberration at the edges of the image is greater with wider-angle lenses. With dome (hemispherical) ports, refraction does not have such an effect underwater, objects do not appear close, the field of view and focal length are preserved. When constructing an underwater housing with a dome port, an additional condition is the perfect centering of the lens and the dome port. Dome ports have to be protected because they can easily be scratched, and are expensive to replace. Therefore, one needs to use a lens protector when not shooting with them.

The equipment (cameras and their characteristics, dome ports, lighting, etc.) used in underwater capturing in different application areas are systematised in a table and are presented at the corresponding link https://lz1ccr.com/?p=12.

Conclusions:

Researchers strive to have the best equipment to achieve high accuracy. Manufacturers come up with new models almost every year; however, a reliably selected camera that provides quality capture in an underwater environment can be used for over 10 years. The leading considerations in camera replacement are the following: increased low-light performance, zero extra noise in the photo, improved focusing speed, and rate of operation. As for those shooting a video, the leading parameters are: the increased video resolution (4k, 8k) with as many 60/120 frames per second as possible without aggressive compression. Under equal conditions, the increase in the megapixels of the camera increases accuracy due to a decrease in the Ground Sample Distance (GSD) value. Since in underwater photogrammetry, capturing is at a close range, it is best to use a wide-angular lens in order to cover more of the object within the frame, and a dome port to obtain the maximum quality from the camera [23, 41, 42]. Raw camera files with more megapixels are larger and, therefore, slower to post-process, yet, they give flexibility for future processing. From the presented overview of the apparatus, it can be concluded that prime lenses are preferred for full frame apparatus (20, 22, 24 mm), and 14 or 16mm lenses for crop sensors combined with dome ports.

3.2.5. Multiple cameras

For a good 3D reconstruction of an object, each point of it must be captured from multiple angles. For an orthophoto of a planar object, it may be sufficient to shoot only at nadir, but an object with complex geometry should also be shot at an angle (oblique capture) to avoid dead zones and ensure maximum model fidelity. Underwater, the duration of capturing the selected object decreases with every 10 meters of depth because of the pressure and its effect on divers. Amateur divers must adhere to the non-compression limits of the dive and comply with the surface rest intervals between consecutive dives. With the increase of depth, the duration over which capturing can be implemented decreases, so this is a sound argument in favour of using more than one camera to perform an optimal capture (larger area of the object, in less time). There should be a good overlap of shots between the dives so that no part of the site is left uncaptured. When capturing with two or more cameras, these can form stereo pairs with a precisely measured base distance between them and additional calibration. For example, the *Sea Array V4* is a three-camera photogrammetry system and features 3 units of *Nikon Z7* (45 MP) cameras with a 14 mm *Rokinon Cine DS* lens and a 230 mm glass dome port, in a custom box and with an underwater scooter mount made by *Marine Imaging Technology.*

Each camera was calibrated first individually and then as stereo pairs. The cameras were tested at the nadir position of the shooting axis. The author concludes that they should also be tested at the oblique position of the shooting axes for a better 3D reconstruction [43].

A study of underwater excavations in low visibility, near the estuary of the Ropotamo river in the Black Sea is of particular interest. The authors share their experience in photographing in low visibility at a distance of less than 50 cm. To overcome this difficulty, they designed and printed out a 3D frame on which five *GoPro Hero 5* cameras were mounted. One camera had a nadir orientation, and the other four were oblique. Thus, they were able to take pictures immediately after each layer of sediment was removed from the bottom [5].

3.2.6. Unmanned remotely operated underwater vehicles (ROVs)

A ROV is controlled from the surface through a connecting umbilical cable. It transmits commands to the ROV, monitors its telemetry, and transmits a video signal to the control panel (telephone, computer, dedicated console or control center). The more expensive models can be powered with current running along the cable or their batteries charged likewise. Thus, these models' stay underwater is prolonged. Micro ROVs can be launched into the water from an inflatable boat or from the shore, and they are easily operated by one person. Large work-class ROVs require a vessel equipped with a crane to drive them in water and retrieve them. Often, they are concurrently operated by two operators, with extra servicing personnel available. ROVs can be divided into the following classes: Inspection class: Micro/Handheld, Medium- sized, and

Intervention class. The Intervention class is subdivided into Light work class and Heavy work class [44]. See the link for further information about the different classes of ROVs https://lz1ccr.com/?p=20.

3.2.7. Autonomous underwater vehicles (AUVs)
AUVs are unmanned; without physical connection to the surface and no control centre, they relying entirely on autonomous power. They are programmed and controlled by an operator. All data collected during the execution of a task is stored on their board. They are equipped with sonars, cameras, depth sensors, magnetometers, sampling equipment, navigation aid sensors, etc., depending on the mission performed [45]. They vary in size and purpose. They can weigh up to several tonnes and reach extreme depths [46]. Some of them travel thousands of nautical miles and remain underwater for several weeks [47]. For AUVs and ROVs to properly execute their mission, underwater positioning and maintaining an accurate course in real time and underwater is of paramount importance. When using more than one AUV, courses must be maintained so that they do not interfere [48].

Safety
Safety is an important element of project and process management. Maintenance, and control of technical equipment and tools are a key factor in achieving it. Ensuring safety is related to the specifics of the activity, the specifics of the terrain and the specific equipment [49].

For a good implementation and safety of processes, it is necessary to consider additional characteristics specific to the individual tools and instruments. Those characteristics have an impact on their efficiency [50].

The successful implementation of any underwater exploration is related to the observance of strict safety procedures - mandatory certified divers, support (under and above water), and a rigid inflatable boat (RIB) in case of emergency [51].

When organizing industrial and scientific diving research, an insurance team is necessary. Optimally, it consists of a leader, a provider, and a supervising diver. In complicated circumstances (descents with supply from the surface, deep water descents, decompression descents), the number of people composing the securing group increases [35].

4. Preprocessing

4.1. Image enhancement
There are several reasons that necessitate radiometric image enhancements. Most of them are related to environmental influences such as loss of color (low contrast), introduction of noise, and blurring in the image caused by the presence of small particles in the water, highly reflective surfaces, and the appearance of waves and currents. There are other operator-dependent factors. These result from keeping the camera steady; otherwise blurred images or noise in them may appear.

Various software approaches are currently available to enhance images before generating the three-dimensional model. These procedures are necessary because the quality of the model and the orthophotomosaic of the object studied depends on the image quality. Restoring natural colours and preserving the continuity of color intensity is very useful in most applications, such as coral reef observation.

White balance is an image enhancement procedure that compensates for color imbalances. These imbalances result from non-ideal light sources as far as the visible spectrum of sunlight is concerned. First, an average RGB colour value is calculated for the entire image, followed by the correction factor for each independent colour channel. There are various development algorithms for white balance. It should also be noted that in most image recognition algorithms, white balance is a very important feature.

Spatial blurring must also be considered in image enhancement. In general, image contrast degradation is mainly due to backscatter. It creates a spatially varying veiled light effect that increases with distance and usually reaches a maximum effect in the image background. An additional factor influencing spatial blurring is the artificial reduction of light power. It is, therefore, appropriate to take this factor (spatial blurring) into account when enhancing images.

Other procedures to improve image quality are related to *colour reconstruction*. The limited penetration distance of certain wavelengths results in colour loss. This causes an imbalance of colour information that is most harmful to the red channel. Combined with the effects of backscattering and light attenuation, a reduction occurs in image contrast and loss of chrominance. Combined with the effects of backscattering and light attenuation, a reduction occurs in image contrast and loss of chrominance. In most of image enhancement algorithms and artificial intelligence approaches, colour is an essential attribute [52].

Image enhancement is a complex task that continues to evolve at a rapid pace. One research work offers various strategies and approaches to improve the quality of photogrammetric products without neglecting their reliability in terms of the object studied (e.g. a wreck) [43].

Another research work presents a comprehensive exploration of image reconstruction approaches obtained through deep ocean capturing [53].

Good results have also been obtained with an approach combining the frequency and spatial domains by first enhancing the image contrast in the frequency domain, then refining the image colour in the spatial domain, and finally merging the contrast-enhanced image with the corrected colour [54].

Two major steps were applied for image enhancement by capturing part of a unit in a nuclear power plant, in an extreme underwater environment. One was occlusion noise removal based on the multi-frame method, and the next one was haze removal based on the single-frame estimation [55].

A network called *Unicolor* is developed which is an underwater image enhancement network via medium transmission-guided multi-colour space embedding. Ucolor achieves superior performance against state-of-the-art methods in terms of both visual quality and quantitative metrics [56]. Review papers exist that focus on image enhancement methods [57].

4.2. Calibration

When working with photogrammetric equipment - digital cameras, the issue arises of image distortions and deformations resulting from the optics and design characteristics of the camera in general. These bring about geometric distortions and therefore it is necessary to perform calibration. This process is very important when non-metric sensors are used. Accurate determining of the focal length (f), the coordinates of the principal point (cx, cy), and the lens distortion parameters (k1, k2, k3, k4, b1, b2, p1, p2) affect the geometric accuracy of the created model. Therefore, small errors in the perspective projection must be eliminated in order to avoid systematic measurement errors.

There are various methods for calibrating digital cameras. One of the most common methods is based on camera self-calibration algorithms. It is suitable even for non-metric sensors. In the self-calibration or auto-calibration process in Computer Vision, no calibration object is used, and the metric properties of the camera and the imaged scene are recovered from a set of images, using constraints on the camera parameters or on the imaged scene. The self-calibrating bundle adjustment is a very flexible and powerful tool for camera calibration and systematic error compensation, and it provides accurate sensor orientation and object reconstruction [58].

Underwater photogrammetric studies require the use of two- or three-dimensional objects (checkerboards, frames, fixture devices) for calibration due to the additional distortions caused by the different refractive indices of the air-water medium, as well as the peculiarities that arise when using flat or dome ports.

Computer vision calibration models typically use reference grids. The calibration matrix is defined using a known array of object points, e.g. checkerboard patterns, two-dimensional or three-dimensional frames (Fig. 2). The material they are made of is also important, as it must have minimal thermal expansion.

Two-dimensional frames are used when the purpose is related to archeology [4], monitoring of red coral colonies [22], reef mapping [59] and others, i.e. when capture is done from approximately the same distance and on the same surface. A portable control frame with a fixed grid or target is placed opposite the measured object to provide calibration corrections as well as positioning and orientation of the camera system relative to the object.

In another type of tasks, where the required accuracy is very important, three-dimensional frames (fixtures)are used. Such a fixture is shown in Figure 2b. These procedures provide a set of intrinsic parameters that can be used as an initial guess during the self-calibration phase when the latter is performed before or during the bundle adjustment in a typical photogrammetric workflow [19].

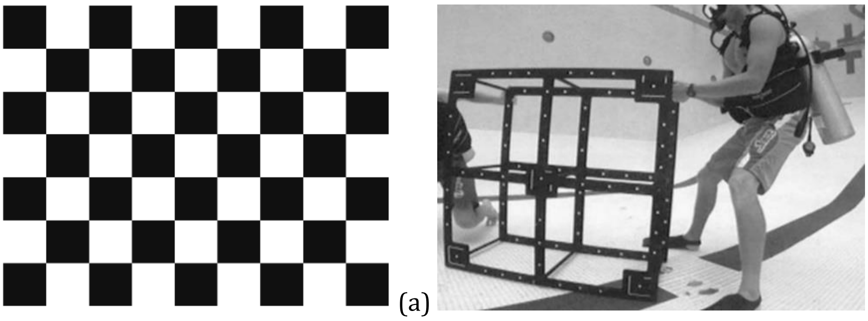
(a) (b)

Figure 2. Black and white checkerboard pattern (a) fixture (b). Source: (b) Shortis, 2015 [60].

Technology continues to evolve, as does research related to port calibration for depth sensing [61, 62]. A new type of calibration frameworks is created [63], along with research aimed at modelling the environment to be used for developing, evaluating, training, testing and tuning refractive algorithms [36] and others [64].

5. Data processing

Modern data processing software solutions use the Structure from motion method [14], which combines established photogrammetric principles with advanced computational methods. A series of overlapping, offset images can be processed through it. These can be obtained at different angles and distance to the study object without the need for information about camera

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positions and orientation. SfM algorithms analyze the image correspondences and camera positions to provide an initial guess of the scene's 3D structure and camera poses.

The methodology includes the following major steps - finding identical (key) points in all overlapping images, connecting the key points, and finally, implementing an iterative procedure known as bundle adjustment to minimise the so-called reprojection error between the locations of the observed and predicted points in the images [65]. The first stage of the SfM approach comprises detecting identical points in all overlapping images and applying the scale-invariant feature transform **(SIFT) algorithm**. This algorithm allows individual images or characteristic points from them to be linked without the need for the images to be of the same scale (i.e. they can be of a different resolution). The algorithm transforms the input images into a set of local specific features that are invariant to the scaling and rotation of the underlying image. However, this initial reconstruction often has errors. This makes it necessary to proceed to the next stage of the SfM approach, namely, **bundle adjustment**. It is a well-known mathematical algorithm used in photogrammetry and computer vision to improve the accuracy and reliability of reconstructions of 3D scenes from multiple images. It is used to correct errors from the initial 3D reconstruction process, including inaccuracies in camera pose, scene structure, or feature tracking. Therefore, the first calculation is that of the reprojection errors for each image, between the computed and the observed image coordinates. An optimisation function is also defined, which is usually the sum of squared (reprojection) errors across all images. Non-linear optimisation techniques are used iteratively to minimise the objective function and to refine the 3D scene structure and camera parameters. At this stage, the interior and exterior orientation parameters automatically extracted from the overlapping images are also computed. In addition, a sparce point cloud is created (based on the homologous points found in the captured images, the three-dimensional coordinates of the object are obtained in an arbitrary coordinate system). Due to the object geometry previously obtained a dence point cloud is created which involves computing a corresponding 3D point for almost every pixel of the image. Subsequently, three-dimensional textured models and surfaces can be generated.

Reference points, such as natural features, artificial markers, or scale bars are used in order to achieve the required accuracy of the model and to keep it in a specific space coordinate system. These points provide the necessary data for the software algorithms to compute the spatial relationships between the images.

Scaling

In many of the studies carried out in the underwater environment, it is of utmost importance to obtain a model which is geometrically similar to the observed object but scaled. For this purpose, scale bars (Fig. 3) located on the object are used. Those are accurately measured and subsequently their lengths are entered in the SfM processing workflow to compute the internal parameters of the camera. Thus, the generated three-dimensional model is scaled but not georeferenced, i.e. the model is then geometrically correct but in relative coordinates.

When two or three synchronised cameras are used, there is no need for scale bars as the scale is computed using the calibration of the camera set.

Georeferencing

To obtain a three-dimensional digital model in a specific space coordinate system, it is necessary to use ground control points (GCP) – Fig. 4. They are evenly positioned on the object by measuring their coordinates (X,Y,Z) which are entered in the SfM processing workflow. For this purpose, a surface buoy system is used whose coordinates are measured with GPS. Depending on the required accuracy, the Z coordinate can either be determined by measuring the distance from the buoy to the control point, through a depth gauge embedded in a dive computer [8], or in another way [66].

Figure 3. Scale bar (D). Source: [67] https://www.pix4d.com/blog/diving-into-underwater-photogrammetry/

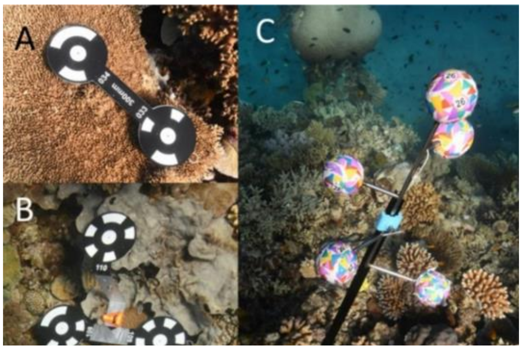

Figure 4. Photogrammetry ground control points: (A) dumbbells, (B)triads and (C) sphere trees.

A further approach to georeferencing is by determining the exact location of the camera. An example of such capturing in coastal shallow waters is the use of a low-tech and low-cost system equipped with a GNSS antenna for accurate positioning in RTK mode as presented in figure 5. It provides high-resolution imagery and facilitates the georeferencing process [15].

The data from underwater capture are processed through commercial professional software. There are fully automated platforms with an intuitive workflow producing high-quality digital models from imagery. The analysis of image processing software derived from underwater capture shows that the best results for underwater object capture are obtained using the *Agisoft Photoscan* and *Reality Capture* programs [68].

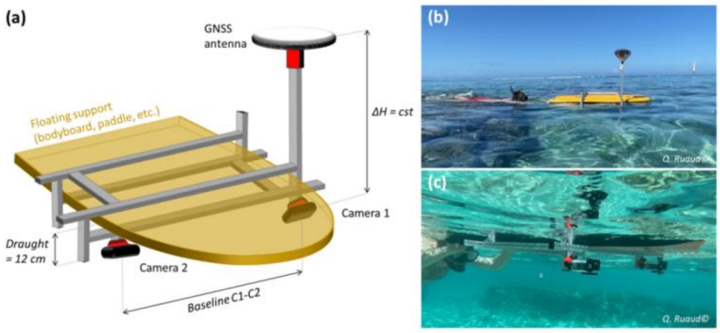

Figure 5. (a) Conceptual diagram of the system, with a structure adapted to a bodyboard holding two GoPro cameras and an RTK GNSS antenna vertically above one of the two GoPros. (b,c) Overwater (b) and underwater (c) views of the system during acquisition. Source: Jaud 2024 [15].

Sophisticated software algorithms embedded in contemporary software, such as the structure from motion method, allow the generation of detailed and accurate digital models of objects in the underwater world, opening up new possibilities and expanding the applied directions of underwater photogrammetry.

6. Applications

6.1. Off- and onshore industry
The issues related to mineral extraction are of utmost importance to people's lives. In the offshore and onshore industry, the inspection, maintenance, and repair of subsea structures depend on their quality operation. Underwater photogrammetry is employed in various activities related to the planning of repairs and maintenance of subsea infrastructure (inspection of pipelines, platforms, and subsea equipment). It is also involved in the development of inspection systems to help the underwater construction industry. It is used to locate and explore mineral and energy resources and to understand the fundamentals of geological and oceanographic processes. In recent years, the introduction of various underwater imaging and real-time inspection systems has been on the increase. One such system designed to operate at a depth of up to 1000 meters has displayed a high accuracy potential in a water basin with clear water [16]. The analysis of another monocular 3D weld reconstruction system in turbid water has demonstrated its capabilities of conducting digital visual testing. Thus, the inspector performs a fully automated, accurate, and objective weld assessment [69].

It is also of interest to perform riser checks on offshore platforms using a Deep Learning technique. Although the capturing has been implemented with UAVs, it could be employed in underwater photogrammetry, borrowing on the Deep Learning techniques [70].

Photogrammetry is also used in underwater construction. In order to ensure safety when monitoring a huge trunk steel pipe that is to be installed at the bottom of the reservoir, a scaled model has been created for simulation purposes. Analyses demonstrate that the photogrammetric approach is flexible, easy to implement, and unaffected by viewing angle, position, or coverage, thus rendering it appropriate for such purposes [18].

Exploration for Oil and Gas Industry Purposes offers an extensive review of optical, underwater surveying methods. They cover a range of application areas and can be used in a variety of tasks as they provide high accuracy and detail. They can be implemented relatively easily but require knowledge related to camera selection, its calibration, and integration for underwater applications. Visual odometry and Visual Simultaneous Localization and Mapping (VSLAM) techniques are also addressed.

The issue of combining optical and acoustic technologies to extend the application capabilities in low visibility conditions is also addressed [17]. A seafloor mapping project with AUV swarms, called CARMA (Mineral resources mapping by AUVs swarms), is also a subject of interest [71].

The solution to several application issues using underwater photogrammetry has confirmed its leading position among the methods used in the underwater environment for the offshore and onshore industries.

6.2. Archeology

Another application of underwater photogrammetry is related to the documentation, study, and popularisation of archaeological sites and cultural heritage [19, 7, 4, 6, 20, 72]. It is crucial to create accurate three-dimensional models of the studied objects (fig. 6) or maps of certain areas (fig. 7), especially since some are threatened with demolition and/or destruction more before they are thoroughly studied.

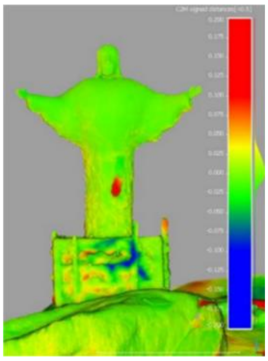

Figure 6. Mesh-to-mesh distanceshowing the damage of the belt of the tunic of Christ in red. Source: Menna 2023 [10]-into-underwater-photogrammetry/

Figure 7. Very high resolution orthophoto from the project's website (http://www.groplan.eu). Source: Drap 2015 [3]

Portable mobile underwater photogrammetric systems based on (vSLAM) technology are of particular interest. Such systems can be used for mapping and creating three-dimensional models. Owing to the comparison between mesh models (the damage of the belt of the tunic of Christ in red) from current and previous imaging of a statue (over a period of 2 years), damage was detected which was most likely due to corrosion [10].

In addition to documenting and mapping, underwater photogrammetry is also used for 4D modelling of archaeological excavations.

The aim is to track the different phases of the excavation work. This facilitates the better management and optimisation of the methodology used and the understanding of the nature of cultural deposition [5].

Architectural sites remain invisible to much of the society. This has prompted the development of virtual museums of cultural heritage, such as the one in Malta [51], and the creation of a database for their systematisation [6]. The development of educational software tied to virtual reality enables an easier understanding of the basics of underwater photogrammetry and its use [73].

6.3 Marine biology, underwater conservation, and ecology

Most of the underwater research is related to the observation and conservation of ecosystems. Assessing the status of coral reefs, tracking their growth and development, monitoring fish populations, measuring the impact of climate on underwater life - these are but a few of the activities that help analyse their status and to undertake effective strategies for the conservation and protection of seas and oceans. The photogrammetric methods and tools used for the needs of marine biology and the protection of the underwater world have developed dynamically over the years [22, 24, 13, 25, 31, 9, 74, 37]. A major part of the research has focused on the mapping and monitoring of coral reefs [75, 76, 28, 8, 77, 26]. This is partly related to global warming, which has a negative impact on marine and ocean life. Photogrammetric methods provide data on the structure and functioning of corals. They are used not only for visual analyses but also for extracting features. Approaches have been developed to automatically obtain morphological information [22]. Photogrammetric 3D models can be used to track ecosystem dynamics, which requires very precise co-registration. Research results show that image acquisition and RSF placement errors contributed the most to the total workflow error (37% and 53%, respectively), while the contribution of co-registration and 3D processing errors was minimal (3% and 7%, respectively). The study also offers guidelines for reducing errors associated with photogrammetric workflows [75].

A significant issue is related to the provision of highly accurate data to track coral growth [23]. There are studies related to the use of underwater macrophotogrammetry to monitor in situ benthic communities at submillimetre scale [78].

The past few years have also seen the wide exploration of approaches based on machine learning [27, 25, 37, 59, 74]. The aim is to automate processes and create an efficient methodology for mapping and assessing the status of the underwater world, as well as for classifying the diversity of plant and animal species.

6.4. Forensics

Investigating crime scenes is a major challenge for forensic investigators since gathering information and documenting an incident is essential for them. The role of photogrammetry in underwater forensics is presented in a study that emphasises its importance and outlines future developments and modernising in this field. Through photogrammetric methods, accurate three-dimensional models can be generated to help detectives improve the quality and efficiency of crime investigations. These digital models can be visualised, viewed, and analysed on a computer, laptop, or mobile device and benefit forensic authorities [29]. With the advent of ROVs, the opportunities for documenting underwater criminal incidents have been on the increase, especially in hazardous and inaccessible locations. Photogrammetric techniques for underwater crime scene investigation are presented in published books [30, 79]. Universities offer certified training for Underwater Crime Scene Investigation [80]. Consequently, researchers who want to deal with underwater forensics can be well prepared since the right equipment along with good training are the prerequisites for the success of any mission.

7. Conclusion

Through underwater photogrammetry, new worlds are discovered and data are made available to various specialists, such as geologists, biologists, ecologists, engineers, forensic scientists, artists, etc. who can analyse and observe various processes and phenomena remotely. In order to carry out real-time capturing or video surveillance, trained personnel are required: scuba divers and/or specialists associated with the management of ROVs or AUVs underwater. They should be familiar with both the environmental conditions and the equipment, as well as have a profound knowledge of photogrammetry. They need to know its nature and principles in order to perform a given capture (of an object or surface) in a certain way and with the necessary parameters for the specific task.

A major part of photogrammetry is related to image processing and obtaining three-dimensional models and orthophotomosaics. The knowledge of the processing algorithms will help create accurate and detailed data that can subsequently be used and analysed as intended.

Therefore, introducing the audience to the basics of underwater photogrammetry is an important task and could facilitate comprehending and using it, as well as promoting its applications. Thus, scuba divers and specialists in various fields can be attracted, their professional interests can be broadened, or they could be re-trained to perform activities related to the off - and onshore industry. It could be beneficial to scuba diving associations by using the information as a basis for training purposes which is related to the promotion of underwater photogrammetry and its applications, etc.

References

[1] Drap P 2012 Underwater Photogrammetry for Archaeology *Special Applications of Photogrammetry* Dr. Daniel Carneiro Da Silva (Ed.) InTech, doi: 10.5772/33999

[2] Erič M et al 2014 The Successful use of temporary underwater 3D documenting methodology: Early Roman barge from Ljubljanica river, Slovenia, Actas del V congreso Internacional de arqueología subacuática, Cartagena *IKUWA* **V** 259-274

[3] Drap P, Erič M, Berginc G, Kovačič R, Pugelj M and Solina F 2015 Underwater Photogrammetry and Object Modeling: A Case Study of Xlendi Wreck in Malta *Sensors* **15** 30351-30384 https://doi.org/10.3390/s151229802

[4] Balletti C, Beltrame C, Costa E, Guerra F and Vernier P 2015 Photogrammetry in maritime and underwater archaeology, two marble wrecks from Sicily *Proc. of SPIE* **9527** 95270M-1 doi: 10.1117/12.2184802

[5] Pacheco-Ruiz R, Adams J, Pedrotti F 2018 4D modelling of low visibility Underwater Archaeological excavations using multi-source photogrammetry in the Bulgarian Black Sea *Journal of Archaeological Science* **100** 120–129 https://doi.org/10.1016/j.jas.2018.10.005

[6] Lesgidi P 2019 Interpreting the Significance of Underwater Archaeological Photogrammetry *Maritime Archaeology Graduate Symposium 29th – 31st March 2019 Short Report Series* doi: https://doi.org/10.33583/mags2019.07

[7] Wright A, Conlin D and Shope S 2020 Assessing the Accuracy of Underwater Photogrammetry for Archaeology: A Comparison of Structure from Motion Photogrammetry and Real Time Kinematic Survey at the East Key Construction Wreck *Journal of Marine Science and Engineering* **8(11)** 849 https://doi.org/10.3390/jmse8110849

[8] Mahamadaly V, Fréchon L, Urbina-Barreto I, Garnier R, Pinel R and Deslarzes K 2021 Underwater Photogrammetry as an Environmental Assessment Tool to Monitor Coral Reefs and Artificial Structures *Offshore Technology Conference* OTC-31025-MS doi:10.4043/31025-MS

[9] Ventura D, Castoro L, Mancini G, Casoli E, Pace D, Belluscio A and Ardizzone G 2022 High spatial resolution underwater data for mapping seagrass transplantation: A powerful tool for visualization and analysis *Data in Brief* **40** 107735 https://doi.org/10.1016/j.dib.2021.107735

[10] Menna F, Battisti R, Nocerino E and Remondino F 2023 FROG: A portable underwater mobile mapping system *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLVIII-1/W1-2023**, 295-302 https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-295-2023

[11] McConnell J, Martin J and Englot B 2020 Fusing Concurrent Orthogonal Wide-aperture Sonar Images for Dense Underwater 3D Reconstruction *IEEE/RSJ International Conference on Intelligent Robots and Systems* Las Vegas USA 1653-1660 doi: 10.1109/IROS45743.2020.9340995

[12] Yakun J, Zhou J, Zhou S, Xie H, Zhang C, Xiao J, Yang C and Sun J 2024 Three-dimentional reconstruction of underwater side-scan sonar images based on shape-from-shading and monocular depth fusion *Intelligent Marine Technology Systems* **2** 4 https://doi.org/10.1007/s44295-023-00013-0

[13] Capra A, Castagnetti C, Mancini F, Rossi P 2020 Underwater Photogrammetry for Change Detection *FIG Working Week 2020* Smart surveyors for land and water management Amsterdam, the Netherlands, 10–14 May 2020 https://api.semanticscholar.org/CorpusID:220614274

[14] Ullman S 1979 The interpretation of structure from motion *Proceedings of Royal Society of London Serie B Biological Science* **203** 405–426

[15] Jaud M, Delsol S, Urbina-Barreto I, Augereau E, Cordier E, Guilhaumon F, Le Dantec N, Floc'h F and Delacourt C 2024 Low-Tech and Low-Cost System for High-Resolution Underwater RTK Photogrammetry in Coastal Shallow Waters *Remote Sensing* **16** 20 https://doi.org/10.3390/rs16010020

[16] Bräuer-Burchardt C, Munkelt C, Bleier M, Heinze M, Gebhart I, Kühmstedt P and Notni G 2022 A New Sensor System for Accurate 3D Surface Measurements and Modeling of Underwater Objects *Applied Sciences* **12**(9):4139 https://doi.org/10.3390/app12094139

[17] Chemisky B, Menna F, Nocerino E and Drap P 2021 Underwater Survey for Oil and Gas Industry A Review of Close Range Optical Methods *Remote Sens.* 13(14) 2789 https://doi.org/10.3390/rs13142789

[18] Jhan J-P, Rau J-Y and Chou C-M 2020 Underwater 3D Rigid Object Tracking and 6-DOF Estimation: A Case Study of Giant Steel Pipe Scale Model Underwater Installation *Remote Sensing* **12** (16) 2600 https://doi.org/10.3390/rs12162600

[19] Calantropio A and Chiabrando F 2024 Underwater Cultural Heritage Documentation Using Photogrammetry *Journal of Marine Science and Engineering* **12** 413 https://doi.org/10.3390/jmse12030413doi:10.3390/jmse12030413

[20] Brown S and Henderson J 2024 Recording the SS *Thistlegorm*: Rapid Multi-Image Underwater Photogrammetric Survey of a Large Second World War Wreck *Journal of Marine Science and Engineering* **12(2)** 280 https://doi.org/10.3390/jmse12020280

[21] Elisa Costa 2019 The progress of survey techniques in underwater sites: The case study of cape Stoba shipwreck *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLII-2/W10** 69-75 https://api.semanticscholar.org/CorpusID:146345371

[22] Royer J-P, Nawaf M, Merad D, Saccone M, Bianchimani O, Garrabou J, Ledoux J-B, Lopez- Sanz A and Drap P 2018 Photogrammetric Surveys and Geometric Processes to Analyse and Monitor Red Coral Colonies *Journal of Marine Science and Engineering* **6** 2:42 https://doi.org/10.3390/jmse6020042

[23] Nocerino E, Neyer F, Gruen A, Troyer M, Menna F, Brooks A, Capra A, Castagnetti C and Rossi P 2019 Comparison of diver-operated underwater photogrammetric systems for coral reef monitoring *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLII-2/W10** 143–150 https://doi.org/10.5194/isprs-archives-XLII-2-W10-143-2019

[24] Marre G, Holon F, Luque S, Boissery P and Deter J 2019 Monitoring Marine Habitats With Photogrammetry: A Cost-Effective, Accurate, Precise and High-Resolution Reconstruction Method. *Front. Mar. Sci.* **6**:276 doi: 10.3389/fmars.2019.00276

[25] Modasshir M and Rekleitis I 2020 Enhancing Coral Reef Monitoring Utilizing a Deep Semi-Supervised Learning Approach *IEEE International Conference on Robotics and Automation (ICRA)* 1874-1880 doi:10.1109/ICRA40945.2020.9196528

[26] Fukunaga A, Pascoe K, Pugh A, Kosaki R and Burns J 2022 Underwater Photogrammetry Captures the Initial Recovery of a Coral Reef at Lalo Atoll. *Diversity* **14** 39 https://doi.org/10.3390/d14010039

[27] Sauder J, Banc-Prandi G, Meibom A and Tuia D 2024 Scalable semantic 3D mapping of coral reefs with deep learning *Methods Ecol Evol* **15** 916–934 https://doi.org/10.1111/2041-210X.14307

[28] Gordon S, Aston E, Lechene M, Harianto J, Bray P, Figueira W, Rivero M and Ferrari R 2023 Field photogrammetry in 4D: Overview & in-field workflow Reef Restoration and Adaption Program (EcoRRAP) Standard Operational Procedure Number 14 (No. 1 of series) *Australian Institute of Marine Science, Townsville* (62) https://doi.org/10.25845/SE7T-PS86

[29] Paba R, Moniz R and Magni P 2023 Optimizing underwater visual records for crime scene investigations in water with clear to reduced visibility *Forensic Science International: Synergy* **6**

[30] Becker R 1995 Underwater Crime Scene: Underwater Crime Investigative Techniques *C Thomas 31*

[31] Rende S et al 2022 Assessing Seagrass Restoration Actions through a Micro-Bathymetry Survey Approach (Italy, Mediterranean Sea) *Water* 2022 14(8):1285 https://doi.org/10.3390/w14081285

[32] Mogstad A, Ødegård Ø, Nornes S, Ludvigsen M, Johnsen G, Sørensen A and Berge J 2020 Mapping the Historical Shipwreck Figaro in the High Arctic Using Underwater Sensor-Carrying Robots *Remote Sensing* **12** (6) 997 doi:10.3390/rs12060997

[33] Erena M, Atenza J, García-Galiano S, Domínguez J and Bernabé J 2019 Use of Drones for the Topo-Bathymetric Monitoring of the Reservoirs of the Segura River Basin *Water* **11**(3) 445 https://doi.org/10.3390/w11030445

[34] Sung M, Kim J, Cho H, Lee M and Yu S-C 2020 Underwater-Sonar-Image-Based 3D Point Cloud Reconstruction for High Data Utilization and Object Classification Using a Neural Network *Electronics* **9** (11)1763 https://doi.org/10.3390/electronics9111763

[35] Krystev I and Ganchev P 2005 Basics of scuba diving Varna *Graphics Ltd*

[36] Nakath D, She M, Song Y and Köser K 2022 An Optical Digital Twin for Underwater Photogrammetry *PFG – Journal of Photogrammetry Remote Sensing and Geoinformation Science* **90** 69–81 https://doi.org/10.1007/s41064-021-00190-9

[37] Shao X, Chen H, Magson K, Wang J, Song J, Chen J and Sasaki J 2024 Deep learning for multi-label classification of coral conditions in the Indo-Pacific via underwater photogrammetry https://arxiv.org/abs/2403.05930

[38] Nocerino E, Menna F 2020 Photogrammetry: Linking the World across the Water Surface *Journal of Marine Science and Engineering* **8** 128 https://doi.org/10.3390/jmse8020128

[39] Calantropio A, Chiabrando F and Auriemma R 2021 Photogrammetric underwater and UAS surveys of archaeological sites: the case study of the Roman shipwreck of Torre Santa Sabina *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLIII-B2-2021** 643–650 https://doi.org/10.5194/isprs-archives-XLIII-B2-2021-643-2021

[40] Teague J and Scott T 2017 Underwater Photogrammetry and 3D Reconstruction of Submerged Objects in Shallow Environments by ROV and Underwater GPS *Journal of Marine Science Research and Technology* 1:005

[41] Menna F, Nocerino E and Remondino F 2017 Flat versus hemispherical dome ports in underwater photogrammetry, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLII-2/W3** 481–487 https://doi.org/10.5194/isprs-archives-XLII-2-W3-481-2017

[42] Capra A, Dubbini M, Bertacchini E, Castagnetti C and Mancini F 2015 3D Reconstruction of an underwater archaelogical site: Comparison between low cost cameras *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W5-2015 67-72 10.5194/isprsarchives-XL-5-W5-67-2015

[43] Calantropio A, Chiabrando F, Seymour B, Kovacs E, Lo E and Rissolo D 2020 Image pre-processing strategies for enhancing photogrammetric 3d reconstruction of underwater shipwreck datasets *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci* **XLIII-B2-2020** 941–948 https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-941-2020

[44] Capocci R, Dooly G, Omerdić E, Coleman J, Newe T and Toal D 2017 Inspection-Class Remotely Operated Vehicles-A Review *Journal of Marine Science and Engineering* **5** 13 https://doi.org/10.3390/jmse5010013

[45] Whitt C et al 2020 Future Vision for Autonomous Ocean Observations. Front. Mar. Sci. 7:697 doi: 10.3389/fmars.2020.00697

[46] Wood S 2009 Autonomous Underwater Gliders *Underwater Vehicles* Austria InTech Vienna 499-524

[47] Jones C, Glenn S and Schofield O 2008 Slocum Gliders Make Historic Voyages *Hydro International 12*(7)

[48] Hegde J, Utne I and Schjølberg I 2016 Development of collision risk indicators for autonomous subsea inspection maintenance and repair, Journal of Loss Prevention in the Process Industries **44** 440-452 https://doi.org/10.1016/j.jlp.2016.11.002

[49] Vladkova B 2020 Best Practices to Improve Construction Site Safety, in the specific conditions of processing plant building *9th International Symposium on Occupational Health and Safety – SESAM 2019* October 3rd 2019 Petrosani Romania Matec Web of Conferences January 2020 MATEC Web of Conferences 305:00014 DOI: 10.1051/matecconf/202030500014

[50] Kostadinova N 2020 Jet fans efficiency in tunnel emergency situations *Sustainable Extraction and Processing of Raw Materials* **1** (https://seprm.com) October Issue 47-52 https://doi.org/10.5281/zenodo.4270086

[51] Gambin T, Hyttinen K, Sausmekat M and Wood J **2021** Making the Invisible Visible: Underwater Malta—A Virtual Museum for Submerged Cultural Heritage *Remote Sensing* **13** 1558 https://doi.org/10.3390/rs1305081558

[52] Muñoz A, Moron-Fernández M-J, Cascado-Caballero D, Diaz-del-Rio F and Real P 2023 Autonomous Underwater Vehicles: Identifying Critical Issues and Future Perspectives in Image Acquisition *Sensors* 23(10): 4986 https://doi.org/10.3390/s23104986

[53] Song Y, Nakath D, She M and Kevin K 2022 Optical Imaging and Image Restoration Techniques for Deep Ocean Mapping: A Comprehensive Survey *Journal of Photogrammetry, Remote Sensing and Geoinformation Science* (PFG) **90** 243-267 doi 10.1007/s41064-022-00206-y

[54] Zhang W, Li X, Xu S, Li X, Yang Y, Xu D, Liu T and Hu H 2023 Underwater Image Restoration via Adaptive Color Correction and Contrast Enhancement Fusion *Remote Sensing* **15** 4699 https://doi.org/10.3390/rs15194699

[55] Qiao X, Ji Y, Yamashita A and Hajime A 2019 Structure from Motion of Underwater Scenes Considering Image Degradation and Refraction *IFAC-PapersOnLine* **52** (22) 78-82 https://doi.org/10.1016/j.ifacol.2019.11.051

[56] Li C, Anwar S, Hou J, Cong R, Guo C and Ren W 2021 Underwater Image Enhancement via Medium Transmission-Guided Multi-Color Space Embedding *IEEE Transactions on Image Processing* **30** 4985-5000 doi: 10.1109/TIP.2021.3076367

[57] Lu H, Li Y, Zhang Y, Chen M, Serikawa S and Kim H 2017 Underwater Optical Image Processing: a Comprehensive Review. *Mobile Netw Appl* **22** 1204–1211 https://doi.org/10.1007/s11036-017-0863-4

[58] Remondino F and Fraser C 2006 Digital Camera Calibration Methods: Considerations and Comparisons. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* **XXXVI** 266–2

[59] Ternon Q, Danet V, Thiriet P, Ysnel F, Feunteun E and Collin A 2022 Classification of underwater photogrammetry data for temperate benthic rocky reef mapping *Estuarine, Coastal and Shelf Science* **270** 107833 https://doi.org/10.1016/j.ecss.2022.107833

[60] Shortis M 2019 Camera Calibration Techniques for Accurate Measurement Underwater
In: McCarthy, J., Benjamin, J., Winton, T., van Duivenvoorde, W. (eds) 3D Recording and Interpretation for Maritime Archaeology. Coastal Research Library **31** Springer Cham. https://doi.org/10.1007/978-3-030-03635-5_2

[61] She M, Nakath D, Song Y, Kosar K 2022 Refractive Geometry for Underwater Domes *ISPRS Journal of Photogrammetry and Remote Sensing* **183** 525-540 https://doi.org/10.1016/j.isprsjprs.2021.11.006

[62] She M, Song Y, Mohrmann Y and Köser K 2019 Adjustment and Calibration of Dome Port Camera Systems for Underwater Vision *German Conference on Pattern Recognition* 79-92 doi:10.1007/978-3-030-33676-9_6

[63] Mufti A, Helmholz P, Parnum I, and Belton D 2023 Introduction and validation of a novel calibration frame *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLVIII-1/W2-2023** 1935–1942 https://doi.org/10.5194/isprs-archives-XLVIII-1-W2-2023-1935-2023

[64] Chen Z, Wang R, Ji W, Zong M, Fan T and Wang H 2019 A novel monocular calibration method for underwater vision measurement *Multimed Tools Appl* **78** 19437–19455 https://doi.org/10.1007/s11042-018-7105-z

[65] Özyeşil O, Voroninski V, Basri R and Singer A 2017 A survey of structure from motion. *Acta Numerica.*26:305-364 doi:10.1017/S096249291700006X

[66] Menna F, Nocerino E, Chemisky B, Remondino F and Drap P 2021 Accurate scaling and levelling in underwater photogrammetry with a pressure sensor *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLIII-B2-2021** 667–672 https://doi.org/10.5194/isprs-archives-XLIII-B2-2021-667-2021

[67] https://www.pix4d.com/blog/diving-into-underwater-photogrammetry/

[68] Vlachos M, Berger L, Mathelier R, Agrafiotis P and Skarlatos D 2019 Software comparison for underwater archaeological photogrammetric applications *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLII-2/W15** 1195–1201 https://doi.org/10.5194/isprs-archives-XLII-2-W15-1195-2019

[69] Kahmen O, Luhmann Th 2022 Monocular Photogrammetric System for 3D Reconstruction of Welds in Turbid Water *PFG* **90**:19–35. https://doi.org/10.1007/s41064-022-00191-2

[70] Salazar D et al 2020 3D photogrammetric inspection of risers using RPAS and Deep Learning in oil and gas offshore platforms *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLIII-B2-2020** 1265–1272 https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1265-2020, 2020

[71] https://www.exail.com/exail-rtsys-and-abyssa-join-forces-for-ocean-floor-mapping-with-auvs/ July 1, 2024

[72] Reich J et al 2021 A novel Structure from Motion-based approach to underwater pile field documentation *Journal of Archaeological Science: Reports* **39** (24)103120 https://doi.org/10.1016/j.jasrep.2021.103120

[73] Doležal M, Vlachos M, Secci M, Demesticha S, Skarlatos D, and Liarokapis F 2019 Understanding underwater photogrammetry for maritime archaeology through immersive virtual reality *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **XLII-2/W10** 85–91 https://doi.org/10.5194/isprs-archives-XLII-2-W10-85-2019

[74] Zhong J, Li M, Zhang H and Qin J 2023 Fine-Grained 3D Modeling and Semantic Mapping of Coral Reefs Using Photogrammetric Computer Vision and Machine Learning *Sensors* **23** 6753 https://doi.org/10.3390/s23156753

[75] Lechene M, Figueira W, Murray N, Aston E, Gordon S and Ferrari R 2024 Evaluating error sources to improve precision in the co-registration of underwater 3D models *Ecological Informatics* **81** 102632 https://doi.org/10.1016/j.ecoinf.2024.102632

[76] Vogler V 2019 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. *In Tagungsband zur Konferenz* Go-3D, 107-120 https://www.researchgate.net/publication/335753920

[77] Bayley D and Mogg A 2020 A protocol for the large-scale analysis of reefs using Structure from Motion photogrammetry *Methods in Ecology and Evolution* **11** (11) 1410 – 1420 doi: 10.1111/2041-210X.13476

[78] Gouezo M, Doropoulos C, Slawinski D, Cummings B and Harrison P 2023 Underwater macrophotogrammetry to monitor in situ benthic communities at submillimetre scale *Methods in Ecology and Evolution* **14** (9) 2494–2509 doi:10.1111/2041-210X.14175

[79] Becker R, Nordby S and Jon J 2013 Underwater Forensic Investigation 2nd ed. *CRC Press.*

[80] https://appliedstudies.fsu.edu/current-students/certificate-programs/ucsi-certificate