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ORIGINAL PAPER

Multi-image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach

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Abstract This article presents a discussion of recent advances in underwater photogrammetric survey, illustrated by case studies in Scotland and Denmark between 2011 and 2013. Results from field trials are discussed with the aim of illustrating practical low-cost solutions for recording underwater archaeological sites in 3D using photogrammetry and using this data to offer enhanced recording, interpretation and analysis. We argue that the availability of integrated multi-image photogrammetry software, highly light-sensitive digital sensors and wide-aperture compact cameras, now allow for simple work flows with minimal equipment and excellent natural colour images even at depths of up to 30 m. This has changed the possibilities for underwater photogrammetric recording, which can now be done on a small scale, through the use of a single camera and automated work flow. The intention of this paper is to demonstrate the quality and versatility of the 'one camera/ambient light/integrated software' technique through the case studies presented and the results derived from this process. We also demonstrate how the 3D data generated can be subjected to surface analysis techniques to enhance detail and to generate data-driven fly-throughs and reconstructions, opening the door to new avenues of engagement with both specialists and the wider public.

Keywords Photogrammetry · Underwater archaeology · Digital survey · 3-Dimensional modelling · Underwater photography · Maritime archaeology

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Introduction

This article presents the results of underwater multi-image photogrammetric survey and subsequent use of 3D data by the authors between 2011 and 2013 and aims to build on the existing literature and trials by underwater archaeologists using photogrammetry (cf. Bass 1966; Green 2004; Drap et al. 2003, 2008; Drap 2012; Mahiddine et al. 2012; Skarlatos et al. 2012; Henderson et al. 2013). Results and work flow are presented herein in order to discuss the impact of this rapidly emerging technique as a tool for accurate site planning and for analysis. Capture of continuous high resolution surfaces, rather than selected points, can open up new avenues of analysis and dissemination and result in faster, cheaper and more accurate and objective surveys of underwater archaeological sites. However the adoption of the technique has been slow due in part to the technical complexity of published work flows. We seek to demonstrate a low-cost and simple approach capable of achieving high-quality results. This approach relies on a single compact camera and use of integrated multi-image photogrammetric software (in the case of these trials, Agisoft Photoscan). This approach is best suited to smaller area surveys but could also be applied to larger surveys with minor modification. Results are derived from case study sites that include an underwater excavation in the southwest Baltic and the survey of the Drumbeg historic wooden shipwreck off the northwest coast of Scotland.

Development of a rapid and reliable method for accurate recording of underwater archaeological sites to similar standards as those applied on terrestrial sites has been a goal of underwater archaeologists since the development of the aqualung. Manual survey using baselines, grids and tapes has been and will continue to be the most important technique both on land and underwater. However manual survey of complex underwater sites can be a very time consuming process and presents challenges in terms of subjectivity and accuracy (e.g. Holt 2003). Terrestrial archaeologists are now able to take advantage of a variety of alternatives such as terrestrial laser scanning (TLS) which offers high resolution results with minimal manual input, and while underwater archaeologists cannot yet exploit TLS the use of marine geophysics and more recently LiDAR (Doneus et al. 2013) are increasingly common. These techniques, however, are costly and limited in the types of sites to which they can be applied.

Photogrammetry, the analysis of 2D images to generate 3D measurements has been around almost as long as the camera (Laussedat 1854, 1859). Until recently it has largely remained highly specialised and expensive. For a more detailed discussion of the technique in a terrestrial context see Verhoeven (2011), Doneus et al. (2011) and De Reu et al. (2013). Within the last decade the advent of multi-image photogrammetric software, capable of automatically resolving the effects of underwater refraction as part of the optical characteristics of the lens and calculating the relative positions of the camera has transformed underwater photogrammetry from a highly technical and costly process to a much more powerful and accessible tool with an enormous value for the recording, interpretation and presentation of underwater archaeological sites.

The term ‘Multi-image Photogrammetry’ is used in this paper to describe a recently developed approach to photogrammetry which allows for the calculation of geometric information from large datasets. This approach is also commonly referred to as ‘Structure from Motion’ but the term multi-image photogrammetry is preferred as it makes a clear distinction between the technique discussed here and other approaches to photogrammetry based on stereo pairs. In multi-image photogrammetry, software is used to compare large sets of images simultaneously and to identify matching features. From this simple matching of features it is possible to calculate both the optical characteristics of the camera used and the relative positions of the matched features.

Background: Photogrammetry, Under Water

The potential value of the application of photogrammetry to survey of underwater archaeological sites was recognised in the earliest days of modern marine archaeology (Bass 1966, 112–118). Bass described a pioneering stereo-photogrammetry survey of a Late Roman wreck undertaken by the University of Pennsylvania in 1964 using paired cameras mounted on a mini-submarine. The resulting measurements were manually processed and used to create a plan of the site. This approach minimised the time required for survey but required extensive manual processing, over 56 h in this case. Until very recently photogrammetric surveys resulted in the recovery of relatively small numbers of selected measurements. Green's (2004, 194–202) review of the technique demonstrated that a high degree of technical knowledge, specialist equipment and manual input was still required to produce relatively few measurements (although Green does record the introduction of digital cameras to the process).

Over the last decade advances in automation of photogrammetry driven by the increasing power of computers have led to an increasing interest by marine archaeologists in photogrammetric survey as a low-cost and rapid tool for marine archaeological survey, as highlighted by Canciani et al. (2002), Skarlatos et al. (2012) and Henderson et al. (2013). The technique is particularly useful for complex features which would be difficult to survey manually and has most often been applied to amphorae wrecks in the Mediterranean (Green et al. 2002; Canciani et al. 2002; Drap et al. 2003, 2008; Diamanti et al. 2011; Skarlatos et al. 2012). A majority of published surveys to date have relied on expensive platforms such as submarines and AUVs and used complex technical work flows (e.g. Ludvigsen et al. 2006) but even where diver-operated cameras have been used these have been tended to be high-end and bulky (usually SLRs) often in pairs or even arrays and utilising strobes and integrated GPS in some cases. As a result of the expense and technical knowledge required, the adoption of the technique has been relatively limited and focused on a small number of sites.

Based on trials carried out and presented below, the authors seek to demonstrate that it is possible to capture 3D models of underwater archaeological features using a single camera operated by a diver and processed in a largely automated way. In addition it is important to highlight that the surveys presented were undertaken without pre-survey camera calibration. No grids, frames or baselines were used as surveys were geo referenced to existing site plans created using traditional methods. We also emphasise the value of recently available consumer-grade compact cameras capable of using natural rather than artificial light even in very dark environments. This reduces the reliance on strobes and the effects of changes in shadow. The work flow outlined here has not been tested by the authors over a wide area (>10 m in area) and may require modification for larger surveys, but it can be shown to produce excellent results at this scale. Use of highly integrated software 'black-boxes' such as Photoscan, in which much of the processing is automated, carries certain risks as noted by Remondino et al. (2012, 40). However bearing these caveats in mind it is clear that this work flow offers significant benefits in technical input, speed of survey and the cost and bulkiness of equipment, and makes it possible to undertake ad hoc photogrammetric survey when an unexpected discovery is made or when other tasks are completed before the end of a dive.

Data Processing

Surveys of the type presented here have been made possible by the development of software capable of automated processing of large datasets of images to produce dense models of surfaces. There are a wide variety of multi-image photogrammetry programmes, from free open-source programs to expensive professional-grade packages. Most of these rely on the Scale-Invariant Feature Transform (SIFT) algorithm (Lowe 1999) which can match features between images despite changes in the scale or orientation of the images. While there were highly technical work flows based on this technique available in the early 2000s these tended to be used for measurement of low numbers of manually selected points. In 2009 the release of Auto desk's 123D Catch (based on the Acute3D engine), marked a watershed in the development of user-friendly integrated multi-image software capable of producing meshes and textures and was followed up by the public release of Agisoft's PhotoScan software in 2010. There are now a wide range of such programmes ranging from expensive professional-grade software requiring a powerful computer to free software relying on cloud-processing. An excellent overview of the capabilities of multi-image photogrammetry programmes, particularly with regard to feature matching (see below), is given by Remondino et al. (2012). After trialing many of these programmes we have come to rely mainly on PhotoScan for its ease of use and capability.

In most multi-image photogrammetric software packages the stages of processing are the same. The first after image capture is 'feature matching'. Once images are loaded into the software a search is made for corresponding points between images. Each image is compared with all the other images and false matches are discarded. In large datasets this stage can be very slow as the number of comparisons rises exponentially with the addition of each image to the dataset. Images may be down sampled if the available processing power is insufficient although this will reduce the quality of the final result. At this stage only a relatively small number of 'tie points', those considered to be the most reliable matches, are identified. Next the relative positions of the points and the camera positions are calculated. The algorithms used in the many of the multi-image photogrammetry programmes have not been published but the process is fundamentally based on simple trigonometry. These algorithms are the heart of any multi-image photogrammetry software and the more robust they are the higher the quality of the result. At the same time the software can compare the tie points to establish the optical characteristics of the lens (if this has not been manually calculated). In the case of PhotoScan, this is based upon Brown's Distortion Model (Brown 1966).

Once the spatial relationships of the cameras and tie points have been calculated it is then possible to reprocess the source images in order to identify a much large set of matching features which are then used to generate a dense point cloud. In surveys undertaken by the authors this typically contains many millions of points and the upper limits are constrained by the number and resolution of images used. This dense point cloud can be used to generate a continuous surface or mesh. For aesthetic or analytical purposes it may then be desirable to return to the original images once more in order to generate a surface texture to drape over the 3D surface. In many of the currently available multi-image photogrammetric programmes, all of the complex calculations required within each of these steps have now been automated. Although some training is still required for processing, the high degree of automation in programmes like Photoscan makes this technique far more accessible to archaeologists than at any time in the past.

Image Capture: Data Acquisition by Photography

The most critical step when undertaking a multi-image photogrammetric survey is to achieve a good underlying dataset. Often there will not be a second opportunity to re-take photos (particularly when documenting excavation). It is crucial to achieve adequate coverage of the subject, to use an appropriate camera setup and to achieve a high signal to noise ratio in the images, where the effects of non-static elements, motion blur, attenuation of light through the water column and digital noise are minimised and the depth of field is maximised. It is important that the archaeologist is familiar with the camera and the principles of exposure as this can mean the difference between an excellent record of a site and a wasted effort.

The first step to consider is camera calibration. Images captured by a camera must be corrected for distortions and vignetting inherent in the design of the camera and lens before they can be used to recover geometric information. Algorithms used in the majority of consumer-grade multi-image photogrammetric software are designed for terrestrial use and to correct for radial distortion which is present in most lenses to a greater or lesser degree. The transmission of light from the water into the air within the housing of an underwater camera introduces additional refraction caused by the change in density of the medium which must be corrected.

Although a number of papers have focused on optical models specifically for underwater use (Rongxing et al. 1997; Lavest et al. 2002; Green and Gainsford 2003), as Drap et al. (2006, 3) states, ‘the deviation due to refraction is close to those produced by radial distortion even if radial distortion and refraction are two physical phenomena of different nature’. In the vast majority of published photogrammetric surveys the calibration of the cameras has been a major element of pre-survey preparation. However, if a hemispheric dome port is used, the additional distortion is also radial and the software is capable of resolving the optical characteristics of the lens directly from the images without prior calibration, relieving us of a significant burden (Fig. 1). Where possible manual calibration is still desirable and some of the more integrated programmes such as Photoscan are capable of importing pre-determined lens parameters. In addition to introducing distortion, refraction under water also causes a strong magnification effect and it is beneficial to use a dome port to reinstate the c. 30° field of view lost when taking a camera under water. Use of a wide angle lens allows the archaeologist to get closer to the subject and reduce the intervening water column, improving the signal to noise ratio in the final images. The trials described in the following section have led to the use, mainly of a wide angle lens, with an in-water corrective dome, between 24 and 28 mm and offering a field of view between 75 and 90°). Use of a wide angle lens also allows for a greater coverage with fewer images or for greater overlap between images. In order for multi-image photogrammetric software to capture a surface in 3D, the archaeologist must understand the concept of coverage and data overlap; this has been discussed by various practitioners who describe overlap requirements of 70 % or greater (Diamanti et al. 2011; Skarlatos et al. 2012), both vertically (top to bottom) and 50 % horizontally (side to side of the photograph). In principal, a minimum of three photos containing the same point is required to triangulate its position in 3D. However it is beneficial to cover the same point numerous times. On land, aerial surveys of wide areas can be undertaken with very low numbers of high resolution images taken at high altitude. This is not possible under water due to the rapid drop off in visibility, meaning that it is necessary to take a large number of images close to the subject, usually not further than 10 m depending on conditions. Capturing an even and complete dataset can be physically challenging for a diver, particularly where a strong current is present. Shutter lag can make this more difficult and it is important

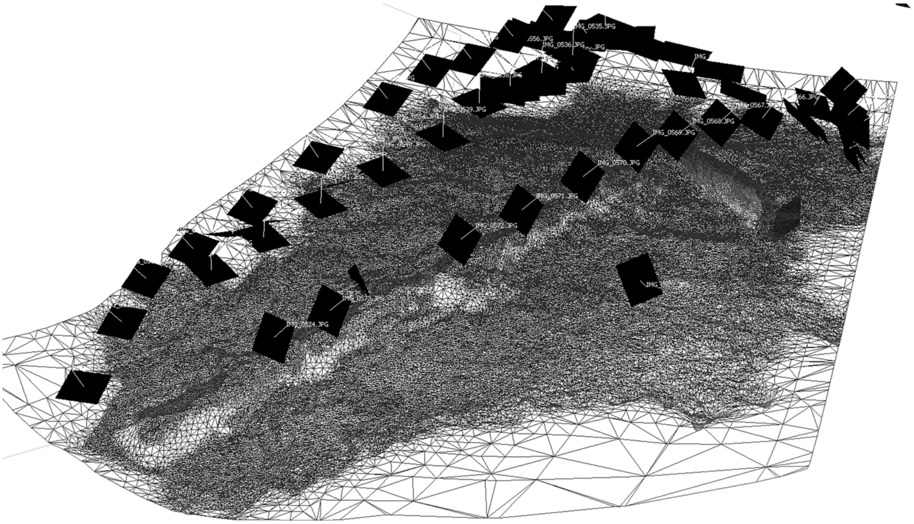

Fig. 1 Camera locations are estimated by the software without any pre-survey optical calibration or post-survey manual feature selection. This image shows the locations of photographs taken by one of the authors while surveying an anchor under water

to choose a camera capable of rapid auto-focus in low light and with a high write-speed memory card. It is sometimes advisable to shoot in a continuous or burst mode, particularly when undertaking linear vertical surveys as this enables ultra-fast recording of dozens or even hundreds of photos very quickly and can be productive even in relatively strong currents. An alternative approach (not attempted in the trials presented here) is to capture video and convert it to stills prior to analysis. Use of video requires consideration of issues related to resolution and file compression algorithms (Hollick et al. 2013).

For submerged sites which contain upstanding features, self-occlusion (where the uppermost surfaces of the subject hide its lower or recessed surfaces) is a significant issue and may make it difficult to achieve total coverage. In such cases a vertical survey approach may be inadequate and the problem can be addressed by taking oblique shots. This may require the diver to get very close to the seabed, and sometimes operate at odd angles and requires good buoyancy control. However these shots are more likely to capture surfaces at a variety of distances from the lens and to represent the same object with different contrast, colour and visibility in different images dependant on its proximity to the camera. This may lead to a failure in automatic feature matching and problems with texture reconstruction. Therefore oblique acquisition should be approached with an understanding of its limitations.

Feature matching, as described above, is one of the core processes carried out by photogrammetric software and can be highly sensitive to non-static scenes. The subject of a survey must be a static object and anything which moves between exposures will worsen the signal to noise ratio, and may prevent automatic feature matching entirely. Although this can be challenging for those undertaking terrestrial photogrammetry it is particularly problematic when surveying under water and moving elements such as other divers and seaweed (bearing in mind the potential for both ecological impacts and for any disturbance of the equilibrium that would negatively impact a site's preservation) must be removed prior to survey.

Changes in lighting which occur between exposures can cause similar problems. Since low light levels are commonly encountered under water, it is tempting to use a strobe (or flash). However a flash will inevitably cast shadows and these will be different in each image. Since the photogrammetry software cannot automatically distinguish between shadow and object, this may affect feature matching and model texture. Henderson et al. (2013) have demonstrated successful use of multiple strobes on shallow sites with low relief, in this case for overcoming the naturally dynamic lighting in shallow water caused by caustics (light passing through waves) and have also highlighted the value of surveying when the sun is low in the sky. The authors have preferred to avoid all use of strobes and to rely on cameras suitable for low light shooting, particularly when including oblique images on high relief sites. This has the added benefit of reducing the bulkiness of the camera.

The issues around visibility and attenuation of light under water are complex and have been discussed in detail in Bryson et al. (2012) and Skarlatos et al. (2012) but it is enough to say here that less light is available at greater depth and that the depth of the water combined with the horizontal distance between camera and subject determine the apparent colour and contrast of the feature. The drop off in both cases is most obvious in the red part of the spectrum, resulting in images with an increasing blue or green cast. Although multi-image photogrammetric software is able to process accurate models of well-exposed images even where those images have a strong cast, it is preferable if possible to correct the images in-camera in order to give the resulting model an easily interpreted texture. Modern digital cameras allow for the use of virtual filters and our first step of image capture has always been to make a manual white balance correction in-camera under water, calibrating against a neutral object, at roughly the same distance and depth as planned for the image capture, allowing for images with a natural hue.

Use of ambient light means that that sensitivity to light of the camera hardware used to capture the images is a crucial consideration. We have focused our efforts on exploiting recent developments in consumer-grade high-performance (in low light) cameras. In many cases we have noticed that a modern compact digital camera is capable of out performing the human eye in low light at shutter speeds suitable for handheld capture. However it is important to understand the limits of this approach and to use the correct settings to maximise the camera's sensitivity to light. Using diver-operated cameras it is generally desirable to limit shutter speed to 1/100th of a second or less to prevent motion blur; Skarlatos et al. (2012) suggest 1/60th and the authors have achieved good results with even slower speeds, however a faster shutter speed will lead to fewer wasted blurry shots and avoid gaps in the final mesh. As we cannot slow shutter speed any further without using tripods, it is necessary to consider the other factors affecting exposure, namely ISO and aperture, and in both cases these can have other side effects that will affect their value for photogrammetry.

Particularly important is the relatively new ability for compact cameras to capture usable images at extremely high ISO. Modern cameras are now capable of light sensitivity far beyond the capability of photographic film. ISO 400 can no longer be considered a 'high' setting and many compact cameras can now achieve low noise images at ISO 6400 and beyond; an increase of 400 % more light sensitivity or four 'stops'. When combined with faster auto-focus and lower shutter lag, capture of well-exposed sharp images using ambient light and fast shutter speeds is possible even in very dark environments.

Aperture can also be adjusted to increase light sensitivity but this will affect the depth of field of the captured images. A shallow depth of field, where objects not within the same plane as the subject appear out of focus is undesirable for photogrammetry. Until recently, achieving a good balance of shutter speed, aperture and ISO under water was beyond the capabilities of compact camera except in the brightest of conditions. DSLR cameras have generally been preferred by underwater photographers (especially for ambient light photography) as their larger sensors and interchangeable, high-quality lenses allowed more light to be absorbed and overall greater image quality. However, depth of field, the distance between the nearest and farthest parts of a scene that are in focus, is inversely proportional to sensor size, with larger sensors resulting in shallower depth of field. The compact camera's small or mid-sized sensor combined with a light-sensitive (or low f-number) lens, will result in a greater area in focus at a lower f-number while still allowing a maximum amount of light to reach the sensor. The difficulty has been that historically small-sensor compacts cannot produce a usable image at high ISO due to distortion, or 'noise' (owing to their small, often lower-quality sensors) and have generally been produced with a built-in lens of >f/3.5. However, to give an example, it is now possible to purchase a consumer-grade compact camera with an f/1.8 lens and a 1″ (diagonal) back-lit sensor. This will perform, in terms of effective aperture (and depth of field), similarly to an f/5 on a full frame DSLR (35 mm equivalent), but will perform as an f/1.8 in terms of sensitivity to light absorbed. In short, this option is highly desirable for underwater photogrammetry as it will absorb the maximum amount of light, while keeping a higher proportion of the photograph in focus. While a larger sensor on an full frame SLR will absorb much more light and yield photos with considerably lower noise at high ISO (>1,600) and with a wide-aperture (low f-number), the larger sensor would produce an image with a very shallow depth of field. This concept has important implications for choice of camera, especially when considering ambient light photography and photogrammetry image acquisition.

Initial Trials

Initial experiments on terrestrial archaeological sites were undertaken by the authors in 2011, progressing from basic indoor tests of small objects to large-scale site-wide surveys generating millions of point with accuracy assessment of results against a RTK surveyed control grid (McCarthy 2011). Underwater tests were carried out in early 2012 using SCUBA gear and handheld cameras in Loch Long, a sea loch on the west coast of Scotland and in a Victorian outdoor swimming pool in Fife. The first test subjects were simply shells or areas of loch bed but gave surprisingly good results and encouraged us to undertake further trials.

Case Study: Faldsled, Denmark (Southwest Baltic)

In the summer of 2012 the authors conducted more complex trials of underwater photogrammetry as part of a team excavating a submerged Ertebølle (terminal Mesolithic) site at Faldsled, south coast of the Danish island of Fyn. The test excavation was directed by the Øhavsmuseet (The Archipelago Museum) and involved a team of eight SCUBA divers operating hand dredges over the course of 1 week. The site had an average depth of 3 m and the average visibility was approximately 5 m. The seabed was characterised by a mixture of open sand and dense sea grass, the latter in constant motion due to the swell. The deposit across the site consisted of a stable sandy unit overlying an older sandy layer containing a very high density of worked lithics and organic material, which in turn lay above a sterile unit of gyttja, an organic deposit derived from peat. Although the principal objective of the excavation was to locate the densest areas of cultural deposits, there was sufficient time to conduct brief photogrammetric trials on some of the dives. The camera used was an inexpensive compact Panasonic Lumix DMC-TS3, waterproof to 12 m without a housing. Three distinct approaches were taken, the first involving linear photographic surveys along the main baselines of the site, the second involving recording of single metre square trenches using large numbers of oblique images taken in a roughly circular pattern. Selected trenches were also surveyed at different stages of excavation. The third approach involved a similar photographic approach but targeted on small individual in situ archaeological finds, including a hand-axe.

Although the first approach to survey along the baseline failed due to the presence of sea grass, the second and third approaches proved successful, generating accurate and detailed models. Processing of the models was undertaken at the end of each day of diving using Autodesk's 123D Catch to test coverage and general results. This software relies on cloud computing and sub samples the images heavily but gave a sufficiently good result to demonstrate that the image data was of adequate quality. The images were subsequently reprocessed at full resolution using Agisoft Photoscan and a dedicated geomatics workstation at WA Coastal and Marine in Scotland. The availability of powerful geomatics workstations meant that no down sampling of images was required. In similar recent examples (Skarlatos et al. 2012, 14) down sampling of images has resulted in far lower point densities.

Using large numbers of images with the camera set to burst mode, an average of 500 shots were taken at selected trenches, in each case taking only around 10 min to capture. One trench was surveyed twice, once during removal of the overlying sand layer and once when the underlying marine clay or gyttja was exposed (Fig. 2). In each case the trench models were output with approximately 5 million polygons (Fig. 3). In the third example a 15 cm flint hand axe was also photographed in situ on the seabed, producing a model of 19.8 million polygons (Fig. 4). Although each dataset took over 24 h of computer time to process, the resulting 3D models of the trenches and the axe were highly detailed and appeared to be accurate representations of the features encountered.

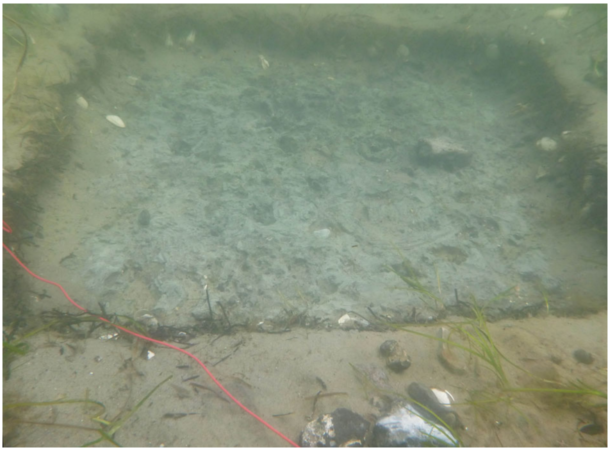

Fig. 2 One of 500 images of a trench which has been fully excavated down to the sterile gyttja. The image is as taken with an in-camera, manual white balance set on site

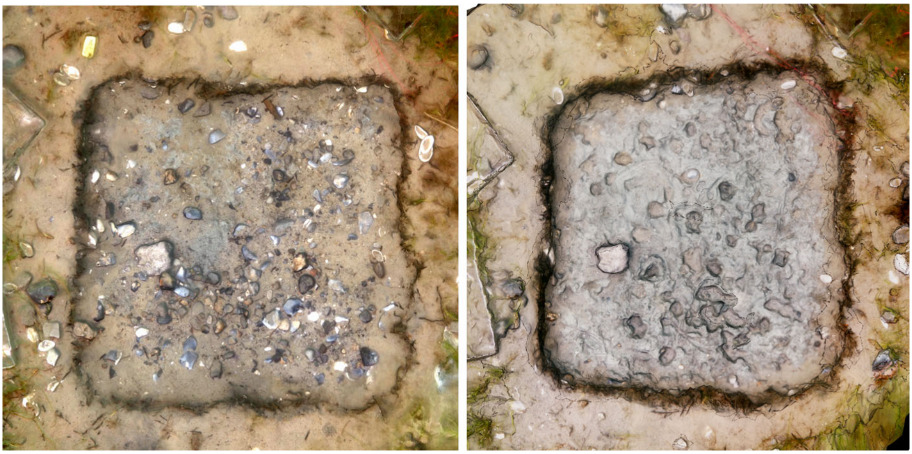

Fig. 3 Orthographic vertical views of the 3D models of a hand-dredged metre square trench at Faldsled, approximately 3 m below the surface. Each of these models is composed of approximately 5 million polygons and has been colour and contrast corrected. The *left* image shows the trench outline after removal of a thin mat of sea grass roots. The image on the *right* shows the trench after removal of all cultural layers with the sterile gyttja, clearly pock-marked with bivalve burrows

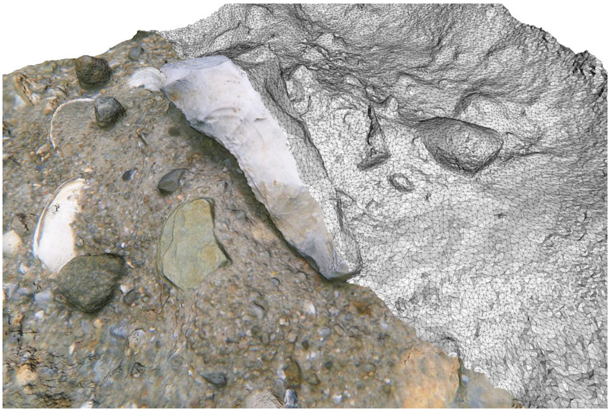

Fig. 4 An oblique view of the 3D model of a 15 cm long Ertebølle hand axe, lying on the seabed in Faldsled, Denmark at 3 m depth. The *left side* of the image above shows a texture-draped high resolution mesh while the *right side* shows a textureless mesh decimated to 100,000 faces so that the individual polygons can be seen

Case Study: Drumbeg, Sutherland (Northwest Scotland)

Building on the results from Faldsled, the authors continued to carry out trials of photogrammetry and research into underwater photography. The lessons learned from the previous survey were put into practice during a week-long dive survey undertaken at Drumbeg on the north-west coast of Scotland in August 2012 (McCarthy 2012). This was an investigation of some possible cannons reported by a local scallop diver. Once again photogrammetry was not the principal focus of the survey but it was possible to devote a small percentage of the underwater time to the capture of photogrammetric data.

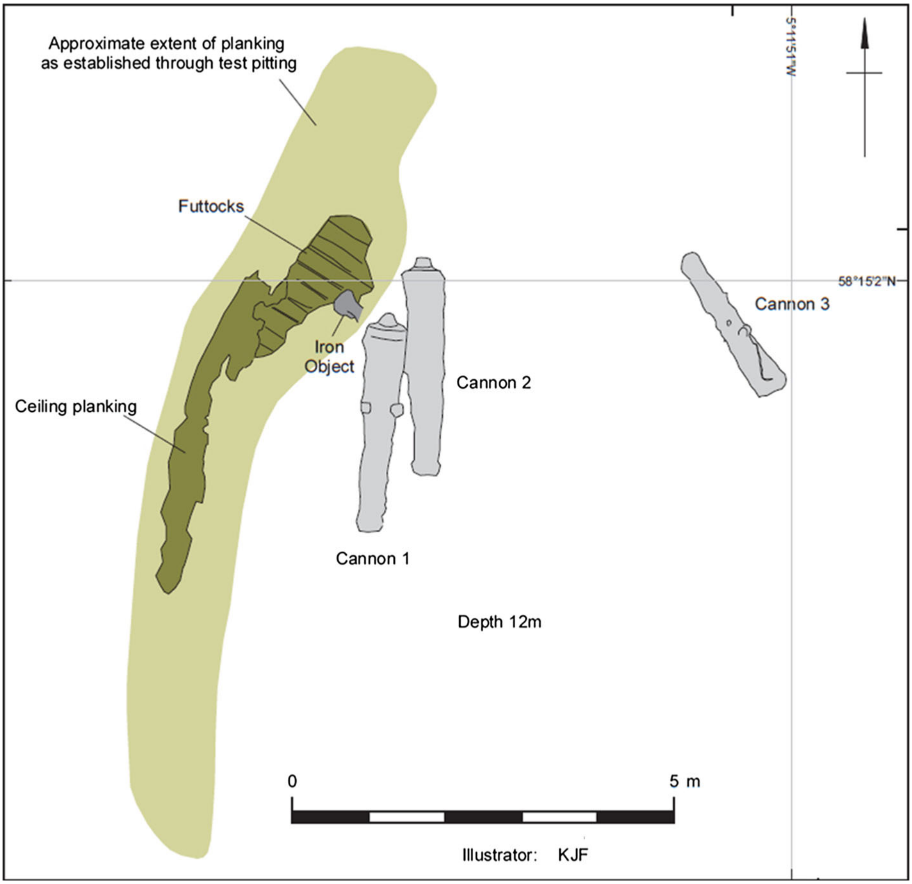

Fig. 5 The shipwreck at Drumbeg

The initial dives identified three lightly concreted cannons at the site overlying a section pf preserved hull, on a sandy seabed at a depth of approximately 13–16 m. Visibility was generally good at 5–10 m. Two of these cannons were approximately 2.2 m long and lay immediately next to each other with a third, smaller cannon (1.9 m length) lying approximately 3 m to the east. Approximately 200 m to the south of the cannons lay a large arrow-shaped anchor. Analysis of the cannons and other finds suggest a seventeenth/eighteenth century date and a northern European origin. All features were measured and drawn in plan on dive slates (Fig. 5).

In order to prepare the cannons and anchor for photogrammetric survey it was first necessary to remove a light covering of seaweed. The approach taken was to photograph the features at a constant distance to reduce changes to colour and brightness which would impact the quality of the final result. The site was initially photographed in a roughly oval pattern around and level with each cannon. Images were captured from above and from as close to the seabed as possible. Although it is important to take photos from low angles to capture detail in overhangs, great care was taken not to disturb the seabed which could reduce visibility and cause debris to settle on the cannons. Finally a series of vertical shots at a distance of approximately 2 m from the seabed were taken across the entire area.

Fig. 6 A model of the three cannons and part of the hull at the Drumbeg wreck site, using around 35 million vertices. The *dark patches* around the cannons are fragments of seaweed which was picked off the cannons before data capture in order to expose the surface and a half metre scale lies between the two cannons on the *left*. It is worth noting that the visibility was poor enough that the divers were unable to see the two cannon on the *left* from the third cannon on the *right*

The resulting datasets were processed at full resolution, again using Agisoft PhotoScan and a dedicated workstation. The data collected proved suitable for our purposes and resulted in two models, the first covering all three cannons and the surrounding seabed (Fig. 6) and the second covering the anchor to the west. Models were exported from PhotoScan in OBJ format with Jpeg textures. These textures were colour and contrast corrected using GNU Image Manipulation Program and Meshlab (Meshlab Visual Computing Lab—ISTI—CNR)[1] was used to produce orthographic plan views of the models.

The location of archaeological features was recorded in the field using a Sonardyne acoustic USBL diver tracking system. Using this information, and hand drawn plans of the site, the 2D renders of the photogrammetric models were brought into ArcGIS and registered to the British National Grid. As photo scales were placed on each cannon prior to image capture it was possible to derive the scale directly from the model.

One of the most surprising results was the successful recovery of accurate 3D data for the anchor. Only a single dive was undertaken on the anchor and this was in poorer conditions of light and visibility compared to the cannon site (Fig. 7). All photographs had to be taken at circa a 1 m distance from the anchor and the full extent of the object was not visible in any single image. As a manual tape survey was undertaken on the same dive there was also insufficient time to clear the light covering of seaweed and the resulting images were also found to be underexposed. Despite this, processing of the JPEG dataset still produced a high-quality model (Fig. 8).

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[1] http://meshlab.sourceforge.net.

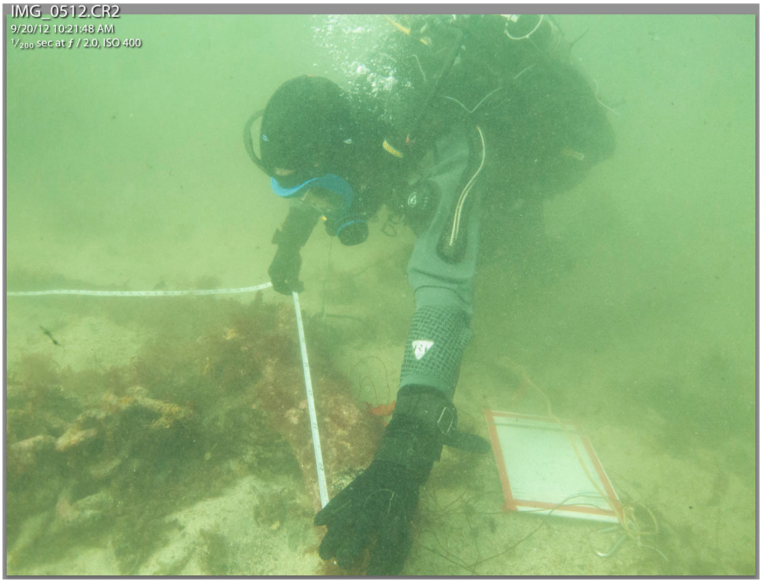

Fig. 7 The conditions at the Drumbeg anchor site. Conditions at the site were not optimal for photography with marine growth, low light and poor visibility

Fig. 8 Processing of the JPEG dataset resulted in an accurate and detailed model of the anchor, clearly showing the diagnostic shape of the anchor head as well as the damaged flukes and a modern chain *left* by the discovers of the site

Accuracy

Accuracy is a key issue for archaeologists and there are a number of relevant guidelines for image capture (e.g. Bryan et al. 2009). The accuracy of a given multi-image photogrammetry work flow is difficult to assess as it depends on numerous factors including but not limited to the distance between the camera and the subject, the optical characteristics of the camera and the clarity of the images. The accuracy of the technique will not only vary from camera to camera and from site to site but may also vary within a single model. For a

Table 1 Comparisons of measurements recovered from the 3D mesh with those recorded on site by the divers

	Cannon 1	Cannon 2	Cannon 3
Muzzle face to base ring			
Diver	2.23	2.26	1.90
Model	2.23	2.25	2.03
% Difference	0	0.44	6.4
Bore			
Diver	0.07	0.05	Too concreted
Model	Too concreted	Too concreted	Too concreted
% Difference	–	–	–
Muzzle face diameter			
Diver	0.27	0.23	0.12
Model	0.29	0.30	0.25
% Difference	6.9	23.3	52
Base ring diameter			
Diver	0.42	0.48	Not recorded
Model	0.43	0.45	0.42
% Difference	2.3	6.67	–
Muzzle face to trunnion centre			
Diver	1.365	Trunnions hidden	1.15
Model	1.32	Trunnions hidden	1.20
% Difference	3.41	–	4.17
Base ring to trunnion centre			
Diver	0.865	Trunnions hidden	0.75
Model	0.88	Trunnions hidden	0.79
% Difference	1.7	–	5.06
Trunnion diameter			
Diver	0.13	Trunnions hidden	0.14
Model	0.10	Trunnions hidden	0.06
% Difference	30	–	133
Length of cascabel and button			
Diver	0.14	0.12	No cascabel/button
Model	0.135	0.14	No cascabel/button
% Difference	3.7	14.29	–

terrestrial subject, comparisons can be made with total station or laser scan data which produce digital outputs with a known and usually very high level of accuracy. For underwater surveys establishment of an accurate control dataset for comparison is much more difficult. Although no such precise control was available for the surveys presented here, a comparison has been made for the Drumbeg cannons between the taped measurements and corresponding measurements taken from the 3D model and it is hoped that this will serve as a useful illustration of some of the potential issues. Table 1 shows a series of standard cannon measurements taken blind from a scaled orthographic plan projection of the 3D model alongside measurements taken at the site by divers (Fig. 9). The

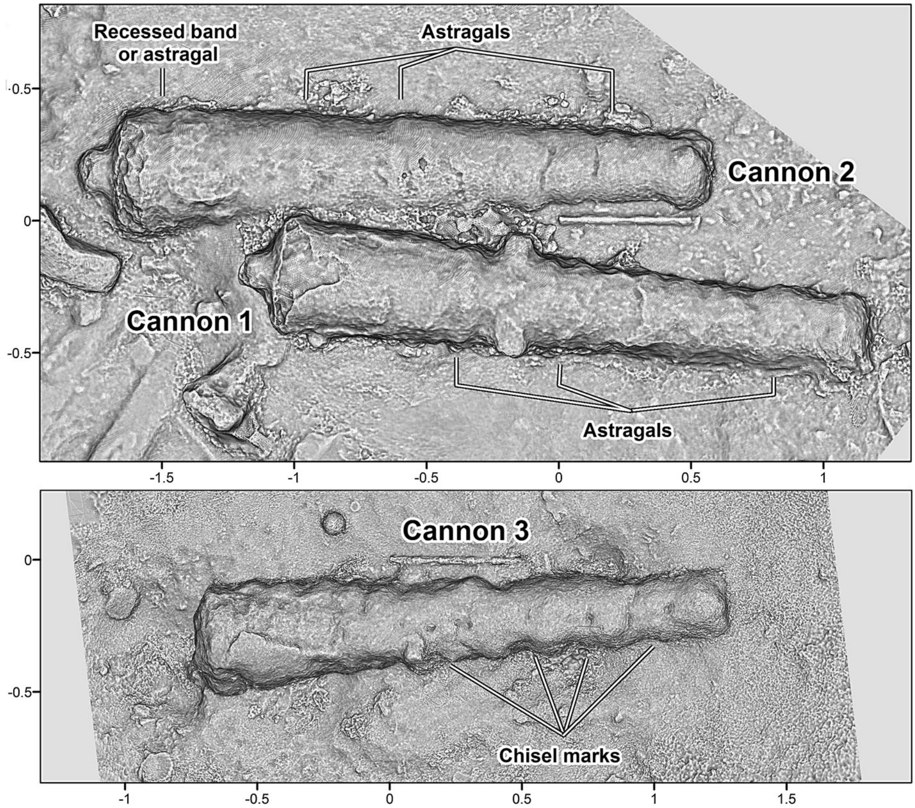

Fig. 9 Orthographic plans of the three cannons at Drumbeg with enhanced surface detail. The accuracy and detail of the models is particularly evident to the *bottom left* of Cannon 3 where the fine detail of a scallop shell has been captured

photogrammetric mesh was scaled with reference to the 1 m scale bar which was placed beside the cannons prior to image capture.

Comparison of the two sets of measurements shows differences as high as 133 % on some measurements. However it is clear that this is more to with the choice of measurement location and the overall distance between them than the accuracy of the model. Small measurements of a few centimetres such as diameter of trunnions are a poor sample for calibration (particularly on a concreted and irregular object) as the diver might choose a slightly different spot to that used on the 3D model. While this is also true of larger measurements this difference is likely to be much smaller proportionally. Therefore the most reliable indicators will be the long measurements as human error will be proportionally lower for longer measurements.

The error for the larger measurements averages around 3 %. For the longest measurements, muzzle to breach, the measurements have a difference of <1 cm, <1 % difference. This, together with the high level of surface detail seen on the cannon and the fidelity with which the geometric shape of the cannon was reproduced (based on a purely visual assessment) suggests that the consistency and accuracy of the model is sufficiently high for archaeological purposes. The authors intend to conduct further benchmarking of this work flow using artefacts of known dimensions.

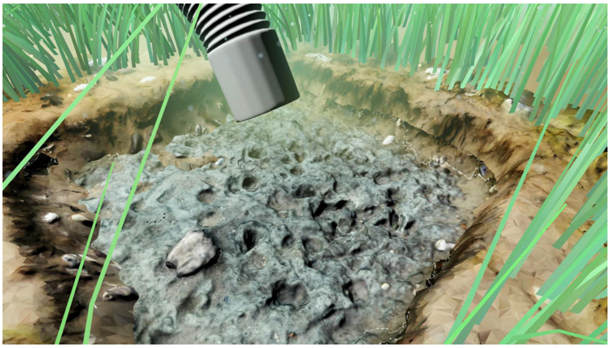

Fig. 10 A still from an animated flythrough of a 1 × 1 m trench at the submerged Ertebølle culture Mesolithic site at Faldsled, Denmark. Two meshes were combined to demonstrate the removal of the upper sediments. Additional elements such as sea grass and a dredger were created and added to the scene

Dissemination and Analysis

We have seen that multi-image photogrammetry can be used to take measurements and create traditional plans and sections of underwater archaeological sites. Another application of multi-image photogrammetry which is novel is its use in creating data-based flythroughs and reconstructions of underwater archaeological sites.

Flythroughs are relatively straight-forward to generate. By importing the textured mesh into a 3D modelling package (in this case, using Autodesk's 3D Studio Max) and applying visual effects such as depth of field and underwater 'fog' it was possible to create realistic flythrough videos that closely matched the experience of diving on the site. Although there are many underwater archaeological reconstructions, these often rely on a small number of measurements or simply on artistic licence. With a dense 3D model directly derived from those features, not only is the resulting reconstruction a much more accurate and objective representation of the feature but it also is far faster to produce. Data-based reconstructions of this kind can be an excellent tool for dissemination and give a very direct experience of the site to those who have not seen the site in person. The models of the trench at Faldsled were also combined into a digital animation where the surface from the earlier stage of excavation was gradually morphed away to reveal the deeper stratigraphy below (Fig. 10).

More interestingly multi-image photogrammetry can be used to undertake analysis in ways that were previously unavailable to marine archaeologists. In the case of Faldsled it was possible to compare the records of the trenches with the drawn outlines and using the known scale of the trenches to take measurements of depths. In the case of the model of the hand axe there is sufficient information for a lithics specialists could carry out a full analysis of the axe without seeing it in person. Animated flythroughs and reconstructions were also created for the cannons and anchor at the Drumbeg wreck site. The reconstructions proved particularly useful in understanding the detail of the artefacts, in particular how a regular geometric shape such as a cannon could fit inside the concreted mass. This process began with a simple model of a cannon barrel which was altered to take up the maximum space inside the concretion while ensuring that it retained a circular section throughout.

The resulting 'ideal' geometric model of the cannon was found to match very closely with illustrations of Swedish seventeenth and eighteenth century 'Fin banker' type cannons

Fig. 11 A still from an animated flythrough of Cannons 1 and 2. In this version parts of the mesh were animated to drop away, revealing reconstructions of the cannons as they might have originally have appeared

Fig. 12 An animated flythrough of the Drumbeg anchor was created with a reconstruction of the artefact as it would have originally looked rising from the mesh as the camera circled it. It was also possible to add lost features such as the damaged flukes and stock

(Stelten 2010, 47). A flythrough animation was then generated showing the concretion gradually ‘melting’ away to reveal models of the cannons as they might have originally appeared (Fig. 11). A similar approach was taken for the anchor, the shape of the mesh being used to constrain the reconstruction and ensuring a higher degree of accuracy (Fig. 12).

High resolution mesh data can also be analysed to recover more detail than can be recorded in the time available under water or in some case more than that visible to the naked eye. The Drumbeg cannon data was processed at the highest resolution available and the models were then exported to MeshLab, a 3D editing tool developed with the support of the 3D-CoForm project.[2] Having 3D data allows for more advanced techniques such as enhancement of surface detail. The colour texture derived from the photographs was removed and the 3D surface rendered with radiance scaling (Vergne et al. 2010) in order to enhance minor variations in the mesh. Despite the high level of concretion on the cannons, this revealed clear traces of four astragals on each cannon which had not been noticed during the manual survey. These are strengthening bands and can be matched with known examples to confirm the identification and dating of the cannons. It is also possible to see other details not recorded by the archaeologists on site such as the minor damage to the surface of cannon two by recreational divers showing five distinct chisel marks.

Summary and Discussion

Technological advances in recent years have led to multi-image photogrammetry developing into an inexpensive, rapid and accurate method for recording of underwater archaeological features. The results presented above were all derived from photographic datasets captured in the space of 20 min or less using handheld consumer-grade cameras operated by archaeologically trained scuba divers who are not professional photographers. Apart from an underwater housing and a dome (wet lens), no specialist rig or other equipment was employed. Of the three cameras trialed during 2011–2013 the most expensive setup is still less than £1,400/$2,000 and the least expensive camera (the housing-less Lumix) only £200/$300. Processing of the data was carried out using more specialist equipment and software including Agisoft PhotoScan, Auto desk 3D Studio Max. These tools are more expensive than the hardware but were already available to the authors and did not have to be factored into the budgets of these surveys. Where budgets are limited there are also much cheaper alternatives, including free multi-image photogrammetry software (such as PMVS/CMVS/Bundler and 3D modelling software such as Blender).

Relative to the considerable overheads of most underwater archaeological surveys, the entire cost of developing a photogrammetry capacity is now relatively minor and should be within the reach of most organisations conducting underwater archaeology. The most significant obstacle to overcome to implement the work flow demonstrated here is that of training. Although many underwater archaeologists have a good knowledge of underwater photography there is a need to adapt normal photographic techniques to multi-image photogrammetry. There is also a need for practitioners to develop an understanding of the type of environments the technique will work in and of how to manipulate the resulting data to produce orthographic plans, 3D flythroughs or for more advanced analysis including realistic data-based models and reconstructions which can be used to bring the public face to face with their underwater heritage. The technique is likely to be useful in other ways and recent work has also highlighted the capacity for photogrammetric survey of submerged monuments photographed through the surface of water (Georgopoulos and Agrafiotis 2012) and for enhancement of underwater AUV navigation (Eustice et al. 2008; Kunz 2012). Given the rate of technological change, an increased interest in public

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[2] http://www.3d-coform.eu.

accessibility of heritage and the practical and economic benefits of underwater photogrammetric site recording it is clear that underwater photogrammetry will become an increasingly important tool for archaeological research and underwater cultural heritage management in the future. The flexibility of the multi-image photogrammetry is its greatest strength and it is vital that a wide variety of work flows and conditions are explored in order to make the most of this powerful technique.

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