
3DMAPPR

A community-based underwater archaeological photogrammetry program in Perth, Western Australia

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Introduction

The Maritime Archaeology Association of Western Australia (MAAWA), in collaboration with Tempus Archaeology (TA) and with the support of the Maritime Archaeology Department of the Western Australian Museum (MADWAM), recently initiated the 3D Maritime Archaeological Project—Perth Region (3DMAPPR). Intended primarily as a community-oriented capacity-building exercise, the overall objectives of the initial stage of the project were twofold: (i) to assess the viability of employing a low-cost underwater 3D photogrammetry package to document maritime archaeological sites; and, (ii) to provide MAAWA members with a set of operational guidelines, training, and experience in underwater 3D photogrammetric recording and data processing techniques. It was intended that avocational ‘citizen scientists’ would then be able to help address current management priorities by making meaningful contributions to the ongoing documentation and monitoring of maritime archaeological sites in the Perth metropolitan region. Combined with another MAAWA initiative (the Shipwreck WA website and smart phone application, <http://www.shipwreckswa.com>), this data has the potential not only to inform ongoing management of maritime archaeological sites, but also to be used as a resource for research, public education and outreach. This paper provides an overview of activities undertaken as part of 3DMAPPR during the first year of its operation. After outlining the project background and rationale, the authors review several case studies and highlight the opportunities afforded by the adoption of underwater multi-image 3D photogrammetry in a non-specialist context.

Project background

The idea of initiating a community-based underwater 3D photogrammetry project developed out of a series of informal discussions between the authors concerning the apparent lacuna in documentation of wreck sites and other aspects of the maritime archaeological heritage in the Swan and Canning river systems. While a considerable number of sites were identified and investigated by MAAWA and MADWAM during the 1980s and 1990s (Scrimshaw 1980), it has to be acknowledged that the current status and condition of many of these sites remain unknown.

The underlying reasons for this are manifold, but can primarily be attributed to:

- a. The lack of any formal or long-term monitoring program;
- b. A limited capacity to accurately document the cause(s), nature, and scale of changes to sites and their immediate environments; and
- c. Potentially too great a reliance on avocational involvement, with all of its concomitant pressures on time, money and expertise.

Given these issues, and the inherent limitations of traditional manual underwater survey and recording techniques, it became readily apparent that there was a need to explore alternative approaches that would enable the non-specialist membership of MAAWA to undertake rapid *in-situ* site assessments and documentation. Necessarily, any such approach would need to meet a number of basic requirements in order to make it ‘fit for purpose’ within the context of a not-for-profit community organisation. These requirements included low financial and technical overheads; appropriate degree of accuracy and precision; and, the ability to utilise inexpensive consumer-grade hardware wherever possible.

Viable low-cost 3D multi-image photogrammetry (3DMIP) in a non-specialist context?

A review of the relevant literature indicated that of the several potential methods available, 3D multi-image photogrammetry was the approach most compatible with the project requirements (Bruno *et al.* 2014; Drap *et al.* 2008; McCarthy 2014; McCarthy & Benjamin 2014; Skarlatos *et al.* 2012; Sorbi *et al.* 2014; Verhoeven 2011; for other techniques, see Drap 2012). The term 3D multi-image photogrammetry (3DMIP) is one of a number of often-unwieldy names that describe the use of 2D image datasets to reconstruct the 3D geometry of an object or scene (Remondino 2014: 63). Current implementations of 3DMIP have been demonstrated to be flexible, robust and accurate solutions for a wide range of heritage documentation projects (Doneus *et al.* 2011), and are increasingly becoming an integral component in archaeological fieldwork, planning and documentation (e.g. Olson *et al.* 2013, Reu *et al.* 2012).

In part, this can be attributed to the considerable number of potential advantages 3DMIP offers over traditional manual recording techniques (Fassi *et al.* 2013). These include:

- Rapidity, objectivity and relative simplicity of implementation;
- Scale independence (i.e. can be used to record objects or scenes of virtually any size);
- High accuracy and precision (under appropriate conditions);
- Ability to employ non-metric photographic equipment;
- Relatively low computing requirements;
- Can repurpose so-called ‘legacy’ imagery;
- Permits sites and their surrounding environments to be documented in a holistic fashion; and
- Reconstruction of an object or scene can be undertaken using data extracted solely from photographic images.

Photogrammetric techniques have long been employed in maritime archaeological contexts, beginning with the seminal work of Dimitri Rebikoff (1972) at the harbour site of Kenchreai near Corinth, Greece, and Donald Rozencrantz at Yassi Ada in Turkey (Bass & Katzev 1968; Rozencrantz 1975). The high costs and overall complexity of implementation at that time meant that these techniques were neither widely adopted nor fully realised in terms of their potential. There followed a considerable lull in the archaeological deployment of 3DMIP that effectively ended only within the last two decades owing in no small part to a series of convergent developments in the fields of computing, digital imaging, photogrammetry and computer vision. These developments served to drive down the cost of computer and imaging hardware, significantly improve instrumentation capability, and make possible highly automated (or ‘black box’) photogrammetry processing workflows. One corollary of this is that ‘photogrammetry... re-emerged as a competitive technology and a resurgence in automated photogrammetric methods’ (Remondino *et al.* 2014: 146; see also Van Damme 2015b: 236–7). Indeed, not only have recent years witnessed a rapid increase in the adoption of 3DMIP within heritage circles at large, but also its effective ‘democratisation’, with use migrating down from purely specialist academic and commercial applications into the public domain.

This latter movement is best characterised by the appearance of a number of community-based photogrammetric recording projects (e.g. Bryan & Chandler 2008; McCarthy 2014; Haukaas & Hodgetts 2016; Rodrigues-Echavarria *et al.* 2009), of which 3DMAPPR constitutes a logical extension.

Nevertheless, it would be misleading to suggest that the use of 3DMIP by non-specialists in underwater contexts is unproblematic. Whilst the technique does involve certain complexities not typically encountered in terrestrial applications, there is nevertheless a persistent but erroneous perception that underwater 3DMIP requires an expensive and somewhat specialised toolkit to implement successfully (McCarthy & Benjamin 2014: 97). For this reason, the authors’ initial objective was to undertake an informal program of testing and evaluating in order to address three broad issues, namely:

- a. Are low-cost software and imaging platforms ‘fit for purpose’?;
- b. What are the optimum operational parameters for recording different types of maritime archaeological sites in a diverse range of environments?; and
- c. What skills and resources are required to generate data suitable not only for the purposes of visualisation, but also to provide informed input into the management of maritime archaeological sites in the Perth region?

In addressing these relatively simple issues, 3DMAPPR can be seen to be concerned less about technological or methodological innovation than it is about establishing an effective ‘operational envelope’ for non-specialists working with limited fiscal and material resources.

Study sites

For the purposes of testing and evaluation, the team identified a number of primary and secondary study sites (Fig. 1 & Table 1). These sites were selected on the basis of representativeness (site size, type, complexity and setting), simple logistics (such as proximity and ease of access), and the provision of a diversity of recording subjects and scenarios. The primary study sites were intended to be the main focus of the testing and evaluation program, and include the iron-hulled SS *Omeo*, World War II landing craft ALC-40 and the remains of Robb Jetty (a wooden cattle handling facility).



Figure 1. Map showing the location of study sites mentioned in the text.

The secondary study sites, comprising the late 19th-century wooden-hulled shipwrecks of *Mayfield*, *City of Perth* and *Eva*, served both as ‘fall back’ options when access to primary sites was not possible, and provided an additional range of testing and training options. MAAWA members had previously recorded several of the study sites during the 1980s and 1990s, the data from which served as a valuable baseline reference for comparison against the results of the photogrammetry program.

SS Omeo (1858–1905)

This a clinker-built iron barque located approximately 40 m off Coogee Beach, where it lies in 2–4 m of water. The ship was wrecked in 1905, when it broke its moorings during a storm and was pushed ashore where it gradually broke up. The wreck site, which encompasses an area of approximately 75 m x 12 m, was provisionally mapped by MAAWA between 1990 and 1992, and has since been the subject of a conservation assessment undertaken by the Western Australian Museum. The wreck is currently protected under the *Historic Shipwrecks Act 1976*, and is set to become one of the metropolitan area’s premier ‘wreck access’ sites (see Koro Brown, 2017, Coogee dive trail opens. *Fremantle Herald*, 28.8: 9 [February 25]).

ALC40 (c. 1943–1944)

This wreck site (18.6 m x 5.4 m) comprises the remains of a 40-ton capacity Australian Landing Craft powered by four 100 hp inboard petrol engines, used to carry vehicles and troops. It is located in the Swan River, 50 m from the shore in approximately 10 m of water, immediately downstream from the East Fremantle Yacht Club. It came adrift in a storm in 1943–4 and sank after being towed back by the Royal Australian Navy and moored in the river. The site was recorded by MAAWA in 1990.

Robb Jetty (1893–1975)

Robb Jetty is located in North Coogee and was built c. 1893 to service the North West cattle trade. Extended to a length of some 166 m and provided with a cattle race and stockyards in 1894, the jetty continued to be variously repaired and extended until the 1960s, at which time it was condemned for shipping. The jetty was subsequently demolished in 1975 in the face of local opposition (Wilkinson 2013: 34–5).

Site	Context	Dimensions	Depth	Status
SS Omeo	Ocean (Coastal)	75 m x 15 m	0–3 m	Primary
ALC40	Sheltered waters (River)	18.6 m x 5.4 m	10 m	Primary
Robb Jetty	Ocean (Coastal)	180 m x 20 m	5 m	Primary
Mayfield	Sheltered waters (River)	22 m x 5 m	5 m	Secondary
City of Perth	Sheltered waters (River)	20 m x 6 m	1–2 m	Secondary
Eva	Sheltered waters (River)	20 m x 5 m	1.5–2.5 m	Secondary

Table 1. Details of study sites.

Mayfield (1899–1945)

The wreck of the *Mayfield* is located in the Swan River, at the base of the limestone cliffs on the western side of Rocky Bay in North Fremantle, and lies at an average depth of approximately 5 m of water. Originally built as an unpowered barge measuring 22 m long and 5 m across the beam, *Mayfield* was registered in 1899 and operated by the Swan Brewery Company. The barge was initially used to transport beer from the brewery to the port to be exchanged for raw materials such as sugar, hops and malt that were returned to the brewery (Wellborn 1987: 79). It finally sank for unknown reasons in Rocky Bay in 1945 where it lies today. The vessel was relocated in 1979 and was recorded by MAAWA in 1980 and 1990 (Cockram 1990).

City of Perth (1871–1908)

The remains of *City of Perth* are located next to the cliffs on the western side of Rocky Bay, lying in approximately 1 m of water and 15 m from the remains of the *Mayfield* (Cooper 2012). It was built as a wooden side-wheel paddle steamer in 1872, measuring 26.5 m long and 5 m across the beam with a displacement of 61.2 tons. The vessel was covered with Muntz metal sheeting, and powered by two 20 hp engines installed and fitted by G. Randell and Company (Dickson 1998: 108). It was used as an observation platform for the 1876 Perth Regatta, where it ‘thronged with gazers’ as it was moored off Mill Point (*The West Australian Times*, 21 April 1876). *City of Perth* was later converted into a lighter and registered with the Harbour and Lights Department in 1898 (Murray 2004: 6) before being abandoned c.1900 (Parsons 1980: 13). The vessel was relocated in 1979 and recorded by MAAWA divers in 1980 and 1990 (Cockram 1990: 22–3).

Eva (1897–1944)

The wreck of *Eva* (20 m x 5 m), located at Point Direction on the North Fremantle area of the Swan River, was first investigated in June 1980 by MAAWA. Built in 1897 as an unpowered wooden barge and lighter designed to transport goods between Fremantle and Perth, its career of cargo transportation ended in 1944 when it was scuttled and used as a slipway. During the 1980s the site was redeveloped, resulting in a jetty being built directly over it.

Methods

Photogrammetry software

A wide and rapidly expanding range of open-source (VisualSfM, the Bundler+PMVS2+CMVSassembly), web-based (123D Catch, Hyper3D/Cubify3D) and stand-alone (Photoscan, Photomodeller Scanner, 3DF Zephyr, RealityCapture) multi-image photogrammetry solutions are currently available. For the purposes of the present project the authors employed Photoscan by Russian developers Agisoft (www.agisoft.com). This package has become something of a *de facto* standard in the field of archaeological photogrammetric documentation, and has been employed in a considerable number of terrestrial and (increasingly) underwater scenarios (Verhoeven 2011; Drap 2012; De Reu *et al.* 2013; McCarthy & Benjamin 2014; Van Damme 2015). Unlike many of its competitors, Photoscan is a cross-platform (Windows X32/X64, OSX and Linux) package that is both simple to install and use, and has a semi-automated multi-stage workflow that can be user-adjusted, giving it a great degree of flexibility. Furthermore, the software is frequently updated and has a very active user-base and support network. Available in two versions that differ considerably in terms of price and capability, issues of cost dictated that the low-end Standard version (currently priced at USD\$179.00 for a stand-alone licence) be used. Extended functionality—including the ability to generate scaled and georeferenced output, orthomosaics, and digital elevation models—was added through the use of third-party open source software, such as Meshlab (Cignoni *et al.* 2008), SFM_Georef (James & Robson 2012) and SAGA GIS (<<http://saga-gis.org/en/index.html>>).

Camera selection

Image acquisition necessarily lies at the heart of any photogrammetry project. A multitude of factors, including the optical qualities of the camera and lens system (resolution, speed, sensitivity, optical correction), the nature of the underwater environment (variable lighting conditions, water quality, contrast loss from absorption, loss of colour information with depth), and the manner in which images themselves are acquired (video sequence or still images, recording strategy, stand-off distance, and image framing), can have a significant impact on the success and overall quality of the project (Hollick *et al.* 2013; Ludvigsen *et al.* 2006; McCarthy & Benjamin 2014; Skarlatos *et al.* 2012; Thoeni *et al.* 2014).

While a number of low-cost camera systems were initially considered for use on the project, the GoPro Hero line of ‘action cameras’ was ultimately selected for further testing and evaluation. The GoPro Hero 3, 3+ and 4 Black Edition models employed in 3DMAPPR are highly portable pieces of equipment, weighing in at approximately 150 g (with housing), and are equipped with a relatively fast f2.8 wide angle lens and 1/2.3-inch type 4:3 sensor capable of capturing images at a resolution of 12 megapixels (MP) and video at up to 4K at 60 frames per second (fps). Additionally, the cameras are waterproof to a depth of 40 m using the supplied housing, reducing the need for additional hardware. While these cameras (particularly older models) have been viewed in an unfavourable light by some researchers owing to issues with optical distortion and its impact on reconstruction accuracy (e.g. Capra *et al.* 2015; Thoeni *et al.* 2014), many of these issues have been addressed through the recent provision of software support for fisheye lens calibration and improved processing algorithms. Indeed, any potential loss of accuracy is likely to be outweighed by tangible benefits such as cost, simplicity of operation, and—above all—ubiquity, with a large number of the MAAWA membership either owning or being familiar with this type of camera.

Recording process

The documentation of each of the study sites using 3DMIP was accomplished in several stages. Initially, a preliminary inspection was made of the site or sites to be recorded, allowing members of the team to familiarise themselves with the location and identify any methodological, logistical or safety issues. This was then followed by one or several recording runs, each of which was carried out in accordance with Rules 3 and 4 of the General Principles of the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage. This ensured that a strictly non-invasive approach was adopted for all field operations undertaken, irrespective of the legal status of the sites involved.

As noted above, the team employed various models of GoPro Hero action cameras for the purposes of image acquisition. These were configured using the in-built intervalometer function to automatically capture images at 0.5-sec intervals at a resolution of 12MP in ‘wide’ mode. While the use of video was considered (and trialled), the time-lapse function was preferred as it embeds EXIF data that can be used to perform camera calibration, requires less

processing (owing to the need to extract still image sequences from video files), and appears less susceptible to motion blur owing to higher shutter speeds (Yamafune *et al.* 2016: 12-13; see Mertes *et al.* 2014: 176, 187; Van Damme 2015b: 234). The use of the time-lapse function also served to reduce the task-loading on divers, allowing them instead to concentrate on other essential tasks such as navigation. As the general working depth of the study sites (and proposed future riverine targets) was less than 20 m, images were captured under ambient lighting conditions. This considerably simplified the recording rig and obviated issues arising from the use of artificial light sources, such as the creation of hard and changing shadows that can create issues for the feature detection and matching algorithms employed by Photoscan.

The recording strategy itself typically involved one or more members of the dive team making a series of longitudinal and transverse traverses (a pattern often referred to as ‘mowing the lawn’) across the site in question and capturing a contiguous series of top-down or ‘nadiral’ images with a substantial overlap (50–75%) and sidelap (50%) (Figs 2 & 3).

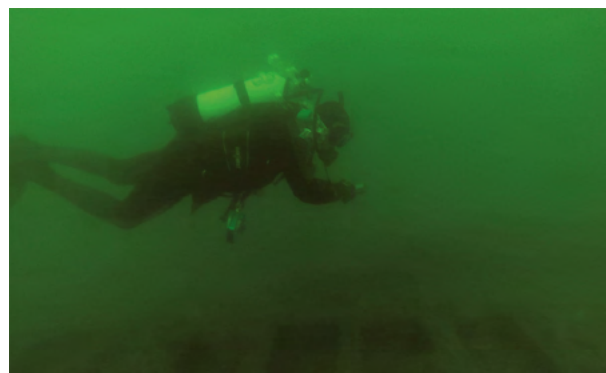


Figure 2. Nicolas Bigourdan preparing to record ALC40.

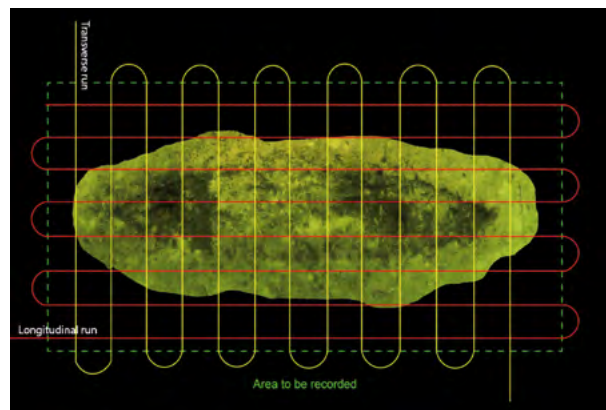


Figure 3. Survey recording strategy.

In the case of 'complex' sites (i.e. those with a significant upstanding remains), the traverses were supplemented with the capture of an additional series of oblique images of the site and/or any specific features (such as the two engines on the wreck of *Mayfield*) in order to provide coverage of any undercuts and/or self-occlusions. Necessarily, this approach was highly flexible, being adapted as and where required, in order to best meet the requirements of each site and its surrounding environment.

In order to maximise the clarity of images, it was initially proposed that a relatively constant stand-off distance of 1.5 m–2.0 m be adopted during recording (Leatherdale & Turner 1988: 35). In practice, however, it soon became apparent that stand-off distances would need to be modified in response to a variety of factors, including water quality/visibility and practical constraints arising from the situation of particular sites. This had a number of implications in terms of how recording was undertaken, given that a decrease in stand-off distance would necessarily reduce the ground sample distance (i.e. the effective photographic 'footprint'), requiring that divers change their swim rate relative to the sea floor/site and modify the spacing of their recording traverses in order to maintain adequate overlap and side lap. This issue was provisionally addressed by developing a set of charts and tables that detailed the relationship between swim speed, stand-off distance, and photographic coverage that allowed members of the dive team to better plan their recording runs. Nevertheless, the issue of successfully navigating sites while maintaining optimum survey coverage remained a constant bugbear, particularly when recording large sites at very close range.

The lack of support for ground control points (GCPs) in the *Standard* version of Photoscan meant that it was not possible to establish a survey network that could be used to constrain, orientate and scale 3D reconstructions (Agisoft 2014). While an attempt was made to employ open source software (SFM_Georef) to address this deficiency, this proved unsuccessful owing to various compatibility issues and overall complexity of implementation. Instead, reliance was placed on a number of very simple scaling controls, such as ranging poles and target markers set out with a known separation (which facilitated greater accuracy owing to the ability to employ longer baseline distances). While these simple methods proved adequate for the purposes of scaling, further elaboration



Figure 4. Simple rig to facilitate scaling and orientation of 3D models.

was required in order to provide a ready means to orientate the models correctly. This involved the creation of a simple demountable rig comprising two arms of unequal length (provisionally 2 m and 1 m respectively) joined at right angles in an 'L' shaped arrangement (Fig. 4). Each of the arms is fitted with a line level and photographic target markers. Mounted on fixed or adjustable legs (depending on the substrate of the site or feature in question), this rig, when manually levelled, is then recorded along with the subject site, where it will provide a visual reference for scaling and orientation transformations. A prototype of this rig has been successfully tested with a refined version to be deployed in future field operations.

Data processing

Primary processing was undertaken using *Photoscan Standard Edition*, which was hosted on an inexpensive Acer Aspire v3-571G laptop computer equipped with an Intel i7-3610QM quad core processor, 8GB of random access memory, and a discrete Nvidia GeForce GT640M graphics card. While this laptop proved suitable for previewing data in the field and processing relatively small batches of 700–800 images, larger datasets necessitated the use of a more powerful desktop computer. In these situations, data processing was undertaken by a Dell Precision T1600 workstation equipped with a 3.10 GHz quad core Xenon processor, 16GB of random access memory, and a Nvidia Quadro 2000 graphics card.

Processing of the images captured during each of the various recording runs was undertaken in several stages. As a preliminary step, all images in each set were manually reviewed, with any considered redundant or unusable owing to issues of quality being removed. In the case of image

sequences recorded under conditions of variable or adverse lighting, additional batch processing was undertaken using Adobe Photoshop. This followed the general procedures outlined by Mahiddine *et al.* (2012), which involved clipping and stretching image histograms to remove saturated highlights and shadows. The processed images were then imported into Photoscan as a single block or 'chunk' for initial alignment and scene reconstruction. Photoscan accomplishes alignment using a technique known as *Structure-From-Motion* (SFM), which is able to simultaneously solve camera pose and the three-dimensional geometry of an object or scene by matching features across multiple overlapping images (Westoby *et al.* 2012: 301–2). After running various point cloud and camera alignment optimisations, a dense point cloud was generated using Agisoft's proprietary implementation of *Dense Multi-View 3D Reconstruction* (DMVR) algorithms, which use the reconstructed camera poses to compute depth estimates for pixels in each pair of matched images. The dense point cloud was cleaned up to remove any extraneous data and then triangulated to form a continuous surface or 'mesh'. The model, which at this point aligned to an arbitrary coordinate system, was manually transformed and placed in its correct orientation using either visual approximation (less accurate) or simple spatial controls (more accurate).

The final step in the workflow involves the generation of a high-resolution surface texture. While the 3D model will itself have been assigned vertex-level colour values during reconstruction, the overall colour rendition and appearance will vary according to the level of detail. The use of high-resolution textures not only gives even low-polygon models a photorealistic appearance, but also allows the user to generate geometrically corrected orthophotos. Photoscan offers a number of different methods for building textures from the source images (e.g. generic, adaptive orthophoto, single photo), the suitability of which depends on the nature of the model and intended end-use(s). Photoscan also allows the user to output the 3D model and any associated texture files in a variety of industry standard formats, that can be used to effect additional processing (such as scaling of models) and generation of output (digital elevation models, contour plots, cross-sectional profiles), using open source third-part applications.

Results

Fieldwork was undertaken between April 2014 and August 2015. During this period, small teams of between two and five people carried out some 15 main recording runs (Table 2). A number of additional recording runs had to be abandoned owing to availability, weather or access issues. The duration of the recording runs (excluding mobilisation and set-up times) differed significantly, ranging from just 9min in the case of run Eva-15-1 to 1hr 3min for OME-15-2, with an average time of approximately 36min. In excess of 45 000 images were captured, with individual recording runs generating anywhere from just under 600 to over 10 000 images. The processing of the image sets for the purposes of 3D reconstruction was in many ways the most time and labour intensive aspects of the process (Table 3). In some cases, it was possible to reduce processing time by working with only a sample of images (there often being a considerable degree of redundancy) and using various combinations of software settings (such as using low accuracy alignment settings and enabling image pair pre-selection). Even so, the processing of a 'typical' set of 600 to 1 000 images at a 4 000 x 3 000 pixel resolution took between 1hr 40min and 4hr 5min to complete using a 64 bit system; larger data sets could take significantly longer (e.g. 11hr 39min in the case of recording run OME-15-3).

The outcomes of processing and 3D reconstruction were mixed. While the majority of data sets were successfully processed to yield a series of coherent, detail-rich and (apparently) geometrically correct 3D models of each of the study sites (Figs 5–7), there were a small number of complete or partial failures. In the case of recording run COP-14-1, processing issues were attributed to the presence across the site of caustic networks (i.e. the undulating patterns of bright light projected onto the sea floor by means of refraction), which are known to cause problems for the feature-matching algorithms employed by photogrammetry software. To address this, it was determined that *City of Perth* and similarly affected sites (such as the shallower portions of SS *Omeo*) be recorded either when the sun was relatively low on the horizon, or under conditions of cloud cover; the success of this simple expedient can be gauged by the outcomes of subsequent recording runs (see Fig. 6 below).

A broadly related problem is characterised by recording run ALC-15-1 (and to a much lesser extent, ALC-14-1), during which sudden short-term changes in water quality/visibility acted to obscure detail in several contiguous frames, creating gaps in photographic coverage. Possible solutions to this scenario include suspending recording until conditions improve or reducing stand-off distance and recording at close-range (e.g. Van Damme 2015b). This latter option, while viable, can nevertheless serve to create other issues in turn.

As discussed above, shallow sites such as *Eva*, *City of Perth* and *SS Omeo* imposed constraints in terms of the stand-off distances employed, requiring that divers reduce both relative swim speed and transect spacing in order to ensure that suitable overlap and sidelap was maintained. This necessarily imposed greater demands on the divers' ability to navigate the site—something that was not always accomplished successfully, as the variable results of OME-15-1, OME-15-2, OME-15-3 and (in particular) ALC-15-2 demonstrate (Table 3). On future recording runs, it is anticipated that a range of navigation aids, such as marker buoys and/or string lines should be employed to help alleviate this issue (see Henderson *et al.* 2013: 247 for a discussion of similar problems).

While it is recognised that problems were encountered with the capture and processing of several image datasets, this should not be construed as an indictment that low-cost photogrammetry is inherently unsuitable as a primary means of documenting maritime archaeological sites. Indeed, the results obtained to date only serve to highlight the several advantages that accrue from the adoption and implementation of low-cost photogrammetry in terms of efficiency, objectivity and accuracy as opposed to traditional manual methods of documentation. For example, using 3DMIP, it has proven possible for small teams to undertake primary documentation of maritime archaeological sites in very short timeframes (typically less than one hour), with processing and data reduction taking only a few hours more (cf. Henderson *et al.* 2013: 249). This stands in stark contrast to past documentation projects undertaken by MAAWA using traditional methods; *SS Omeo*, for example, took several years and hundreds of hours of dive time to complete, resulting in the production of a drawn plan of uncertain veracity (MAAWA 1992; Fig. 8). Similarly, 3DMIP can be seen to provide a far more objective and holistic method of documentation owing to the fact that photographic



Figure 5. 3D model of *SS Omeo*.



Figure 6. 3D model of *City of Perth*.

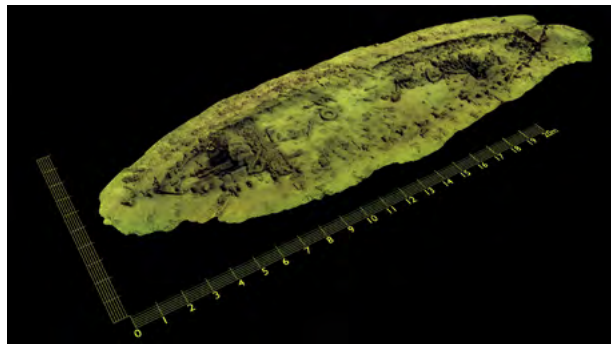


Figure 7. 3D model of *Mayfield*.

images 'provide an unbiased and unselective archive of information at known times independent of human memory or foresight' (Leatherdale & Turner 1988: 35; see Holt 2003). This latter point can be illustrated by reference to a line drawing of *ALC40* generated by MAAWA in 1990 (Fig. 9), which is not only somewhat 'idealised', but also misrepresents the condition of the fabric of the wreck (particularly in the bow area), thereby reducing its value to that of an artistic 'impression' rather than a document that can be used for scientific purposes.

The creation of simple line drawings such as these can be construed as a form of 'black-boxing' (Latour 1999) in which a series of complex three-dimensional

Recording run	Date	Site	Water conditions	Lighting conditions	Stand-off distance(s)	Camera images acquired	No. of control	Scaling	Duration
OME-14-1	30/04/2014	Omeo	Good	Bright/variable	0.5–2 m	GoPro Hero 3 Black	556	N/A	0h 14 m
OME-15-1	15/02/2015	Omeo	Good	Bright/variable	0.5–2 m	GoPro Hero 4 Black	3215	2-m pole	0h 36 m
OME-15-2	23/04/2015	Omeo (run 1)	Good	Bright/variable	0.5–2 m	GoPro Hero 4 Black	5570	2-m pole	1h 03 m
OME-15-3	23/04/2015	Omeo (run 2)	Good	Bright/variable	0.5–2 m	GoPro Hero 3 Black	4461	2-m pole	0h 40 m
ALC-14-1	12/12/2014	ALC40	Moderate	Dark/diffuse	1–1.5 m	GoPro Hero 3 Black	3670	1-m pole	0h 36 m
ALC-15-1	28/05/2015	ALC40	Moderate	Dark/diffuse	1–1.5 m	GoPro Hero 3 Black	5298	1-m pole	0h 46 m
ALC-15-2	5/06/2015	ALC40	Poor	Dark/diffuse	1–1.5 m	GoPro Hero 3 Black	5377	1-m pole	0h 44 m
ROB-14-1	4/12/2014	Robb Jetty	Good	Bright/diffuse	2-3 m	GoPro Hero 3 Black	5767	N/A	0h 56 m
ROB-15-1	16/10/2015	Robb Jetty	Poor	Bright/diffuse	2-3 m	GoPro Hero 3 Black	N/A	N/A	N/A
MAY-14-2	12/12/2014	Mayfield	Good	Bright/diffuse	1–1.5 m	GoPro Hero 4 Black	1438	N/A	0h 14 m
MAY-15-1	18/08/2015	Mayfield	Good	Bright/diffuse	5 m	GoPro Hero 4 Black	1128	N/A	0h 12 m
COP-14-2	12/12/2014	City of Perth	Good	Bright/dynamic	1–1.5 m	GoPro Hero Black 4	1-m pole	0h 14 m	0h 14 m
COP-15-2	18/08/2015	City of Perth (run 1)	Good	Bright/dynamic	1–1.5 m	GoPro Hero 4 Black	1872	1-m pole	0h 21 m
COP-15-3	18/08/2015	City of Perth (run 2)	Good	Bright/diffuse	1–1.5 m	GoPro Hero 3 Black	1516	1-m pole	0h 13 m
Eva-14-1	27/08/2014	Eva	Good	Variable/diffuse	1–1.5 m	GoPro Hero 3+ Black	736	2-m pole	0h 13 m
Eva-14-2	11/09/2014	Eva	Good	Variable/diffuse	1–1.5 m	GoPro Hero 3 Black	2452	2-m pole	0h 24 m
Eva-15-1	12/05/2015	Eva	Good	Variable/diffuse	1–1.5 m	GoPro Hero 3+ Black	966	2-m pole	0h 09 m

Table 2. Summary details of main recording runs.

Recording run	No. of images processed	No. images aligned	Alignment setting/ no. tie points	Dense cloud setting/ no. points	Mesh setting faces/vertices	Total time processing	Comments
OME-14-1	544	521	M+PD (69 595)	M (5 637 479)	M (1 120 827/562 053)	01h 17m 27s	Successful
OME-15-1	1 760	1 642	L+PD (235 095)	L (28 505 457)	L (5 579 918/2 794 928)	07h 24m 32s	Successful; some gaps in coverage
OME-15-2	1 996	1 843	L+PD (546 795)	L (38 397 315)	L (7 507 773/3 757 340)	10h 53m 13s	Successful; some gaps in coverage and possible deformation
OME-15-3	2 215	1 904	L+PD (415 059)	L (42 456 724)	L (7 122 098/3 567 566)	11h 39m 36s	Successful; some gaps in coverage
ALC-14-1	1 833	1 509	L+PE (132 293)	M (7 129 342)	L (16 304 255/8 156 458)	04h 18m 32s	Successful; minor gaps in coverage along south side of wreck
ALC-15-1	2 634	2 335	L+PD (182 151)	L (19 367 602)	L (3 873 519/1 941 930)	11h 32m 19s	Failure; reconstruction errors across port side of wreck
ALC-15-2	2 592	2 003	M+PE (410 297)	L (3 409 829)			Failure; significant gaps owing to sub-optimal coverage
ROB-14-1	914	911	L (280 233)	L (14 003 737)	L (2 769 933/1 388 079)	05 h 36m 02s	Successful
ROB-15-1	N/A	N/A	N/A	N/A	N/A	N/A	Failure; recording run discontinued owing to poor conditions
MAY-14-2	705	677	L (178 092)	L (18 390 175)	L (2 720 876/1 362 552)	03h 27m 14s	Successful
MAY-15-1	367	366	M (61 037)	M (11 010 534)	M (2 143 759/1 074 312)	01h 05m 48s	Successful
COP-14-2	613	37	N/A	N/A	N/A	01h 30m 08s	Failure owing to strong caustic networks
COP-15-2	934	718	L (89 381)	M (28 334 106)	M (5 660 083/2 832 809)	04h 05m 04s	Successful
COP-15-3	751	598	M+PE (163 220)	M (38 320 554)	M (7 698 908/3 853 651)	02h 27m 43s	Successful
Eva-14-1	647	647	L+PD (100 637)	M (14 991 687)	H (2 967 367/1 487 054)	03h 09m 58s	Successful
Eva-14-2	571	571	H+PE (379 616)	M (58 204 576)	M (11 541 103/5 776 765)	01h 40m 03s	Successful
Eva-15-1	966	963	M+PE (196 105)	M (34 164 517)	M (1 930 492/966 700)	02h 19m 30s	Successful

Table 3. Summary details of photogrammetric processing ('L'=low, 'M'=medium, 'H'=high, 'PE'=pair selection enabled, 'PD'=pair selection disabled).

spatial relationships are collapsed and simplified for the purposes of generalised description or depiction. The use of 3DMIP, on the other hand not only allows such relationships to be documented in considerably greater detail, but also facilitates scientific analysis and interrogation in a way that is not possible using two-dimensional data. For example, using nothing but open source software, it is possible to scale 3D models generated by the standard version of Photoscan (Meshlab), generate digital elevation models (SAGA GIS), create detailed contour plots and cross-sectional profiles (Quantum GIS), and undertake a wide variety of other analyses (including diachronic comparison sea floor and wreck surfaces) (Fig. 10). To make these types of analyses viable it is necessary to ensure that data generated by means of low-cost implementations of 3DMIP are both accurate and reliable. However, as noted by McCarthy and Benjamin (2014: 107):

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.

While these issues will require further benchmarking under controlled conditions, some general observations can be made regarding the relative accuracy of models derived from photogrammetry in the absence of a survey control network. A case study reported by McCarthy and Benjamin (2014), involves a small cluster of cannon that were identified during a dive survey at Drumbeg in north-west Scotland. These items were recorded using photogrammetry and conventional techniques. A subsequent comparison of direct and photogrammetry-derived measurements showed a wide range of variance, ranging from 0 to 56%. Some of the larger errors were considered to have been the result of human error during recording; indeed, the error for the larger and more reliable measurements taken was found to fall within 1–3%. They concluded that the ‘consistency and accuracy of the model is sufficiently high for archaeological purposes’ (McCarthy & Benjamin 2014: 109; cf. Van Damme 2015b: 236). Mertes *et al.* (2014: 183–6), in their evaluation of using photogrammetry to generate 3D models of wrecks in the Great Lakes employing ‘legacy’ video footage, reported similar findings, with errors ranging between 1.6% and 18.89%; it was also observed that measurement

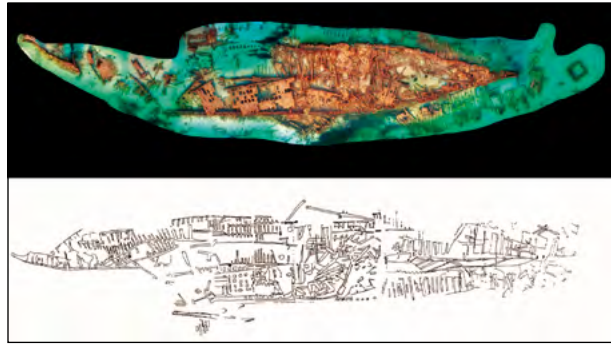


Figure 8. SS *Omeo*: comparison of textured photogrammetric model generated as part of 3DMAPPR (top) and a line drawing compiled by MAAWA during the 1990s (bottom).

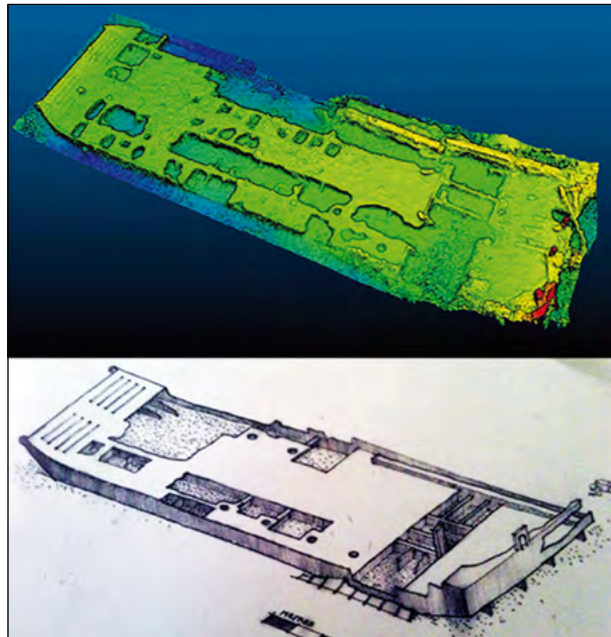


Figure 9. Comparison of photogrammetric model and artistic rendering of *ALC40*, highlighting the issue of objectivity in site recording.

error increased as an inverse function of object size.

The results obtained during the course of the present investigations are broadly consistent with these findings. For example, a comparison of several ‘blind’ measurements taken from scaled three-dimensional models of *ALC40* and *SS Omeo* and direct measurements taken independently by members of the recording team yielded errors of approximately 1% over distances between 0.64 m and 18.69 m (Table 4); the very low error estimates (equating to distances of 1–2 cm) can be attributed to the use of clear and unambiguous measurement points.

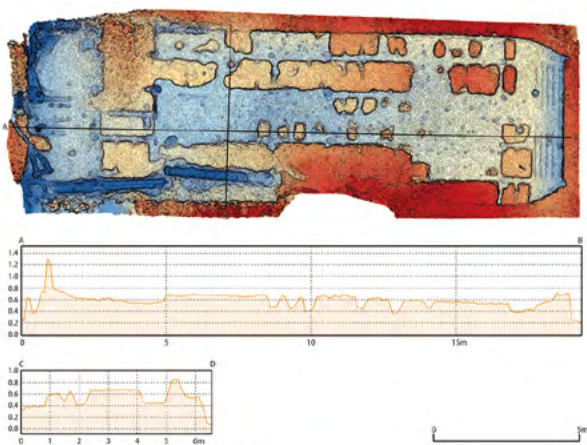


Figure 10. Contoured digital elevation model and profiles generated for *ALC40* using Quantum GIS (open source software).

The potential accuracy of photogrammetry-derived data was also demonstrated by the current authors' ability to successfully overlay datasets for *ALC40* and *City of Perth* that were captured several months apart. However, analysis of other models suggests that in some cases the lack of a survey control network has allowed non-linear errors to propagate.

In the case of *SS Omeo*, for example, the model generated from data captured during recording run OME-15-2 appeared to exhibit a degree of curvature not evident in other models (i.e. those from recording runs OME-15-1 and OME-15-3). In order to investigate this further, the three separate models were imported into Meshlab, where they were trimmed to a consistent spatial extent and aligned using 24 common features. The transformational matrix of the models was then 'frozen' in order to maintain their positions relative to one another, and the models exported. The models were then imported into the CloudCompare package, which was used to compute the 'distance' between each of the meshes, using OME-15-3 as the reference mesh.

The results indicated that while both OME-15-1 and OME-15-2 diverge from the reference mesh, this is particularly pronounced with the latter, which shows a deviation in the vertical plane of approximately +0.9 m at the bow and stern of the wreck (Fig. 11). This level of variation between meshes that otherwise appear geometrically accurate has troubling implications for the use of photogrammetry-derived models in monitoring maritime archaeological sites, given that changes in fabric and environment are likely to occur on the centimetre-scale. Necessarily, additional testing under controlled conditions will be required in order to better assess this issue.

Training and dissemination

Towards the end of the testing and evaluation phase of the project, two one-day workshops were convened at the Shipwreck Galleries of the Western Australian Museum, Fremantle, on 5–6 September 2015. These were undertaken primarily to facilitate the second major objective of 3DMAPPR, namely the provision of training to MAAWA members in underwater 3DMIP recording and data processing techniques. It was hoped that the provision of such skills would not only allow MAAWA members to meaningfully engage in the ongoing recording and preservation of local underwater and maritime cultural heritage, but also engender a sense of 'ownership'. As Muckelroy (1980: 186) explains, the concept of public ownership is a basic principle relating to cultural heritage generally, noting that 'the public (divers in particular) should be encouraged to become involved in the protection and investigation of underwater sites, particularly in order to maintain a public interest in them'. This is particularly important and relevant for Australia owing to the fact that it was this sector of the community (i.e. divers) that lobbied legislators 'to develop protective measures and provided the impetus for maritime heritage programs around the country' (Anderson *et al.* 2006: 139).

Site	Direct measurement	Measurement from Model	Difference
<i>ALC40</i> length	18.69 m	16.68 m	0.01 m (1%)
<i>ALC40</i> width	5.66 m	5.66 m	0 m (0%)
<i>SS Omeo</i> Pt A–B	2.28 m	2.28 m	0 m (0%)
<i>SS Omeo</i> Pt C–D	0.64 m	0.63 m	0.01 m (1%)
<i>SS Omeo</i> Pt I–J	2.06 m	2.08 m	0.02 m (1%)

Table 4. Comparison of direct measurements and measurements derived from scaled photogrammetric models of *ALC40* and *SS Omeo*.

The workshops were attended by a total of 12 participants, comprising divers and non-divers. Structured in two parts, the first component aimed to provide a non-technical introduction to 3DMIP, and touched upon issues ranging from data management and basic image processing through to techniques for generating scaled and oriented 3D models using open source software. This was accomplished using a combination of pre-compiled 'dummy' datasets and guided practical exercises on terrestrial targets. The second component involved a series of in-water practical exercises on the *City of Perth* and *Mayfield* wreck sites in Rocky Bay, North Fremantle. On this occasion, two boats were used to transport the participants to and from site. These were crewed by several qualified personnel who were on hand to provide dive and safety supervision and guidance on recording. In total ten participants dived or snorkelled *City of Perth* and *Mayfield*, completing a number of recording runs using either one of several provided GoPros, or their own personal cameras. Subsequently, participants were encouraged, where possible, to process their own data (using workshop training documents, open source software, and other materials hosted on a shared DropBox folder) and post the results on the MAAWA and other social media networks.

The use of social media has been an integral part of the project from its inception. In particular, the team has been keen to promote an 'open science' philosophy, with its emphasis on transparency, cooperation, skill-sharing, and capacity-building (Nielsen 2009: 32). Towards this end, a dedicated Facebook page (<<https://www.facebook.com/groups/687120911380215/?fref=ts>>) was established early in the life of the project (Fig. 12). With over 600 members at the time of writing, this page has provided a forum for sharing up-to-date news regarding 3DMAPPR, present challenges encountered and the solutions developed, invite participation and comment, and post photographs and video footage of each of the recording runs. Generated output, such as animations and 3D models were similarly uploaded, either to Facebook or Sketchfab (<www.sketchfab.com>), a website that enables users to display and share 3D content online. The results of the projects have also been promoted through academic and popular channels, such as public lectures, and conference presentations.

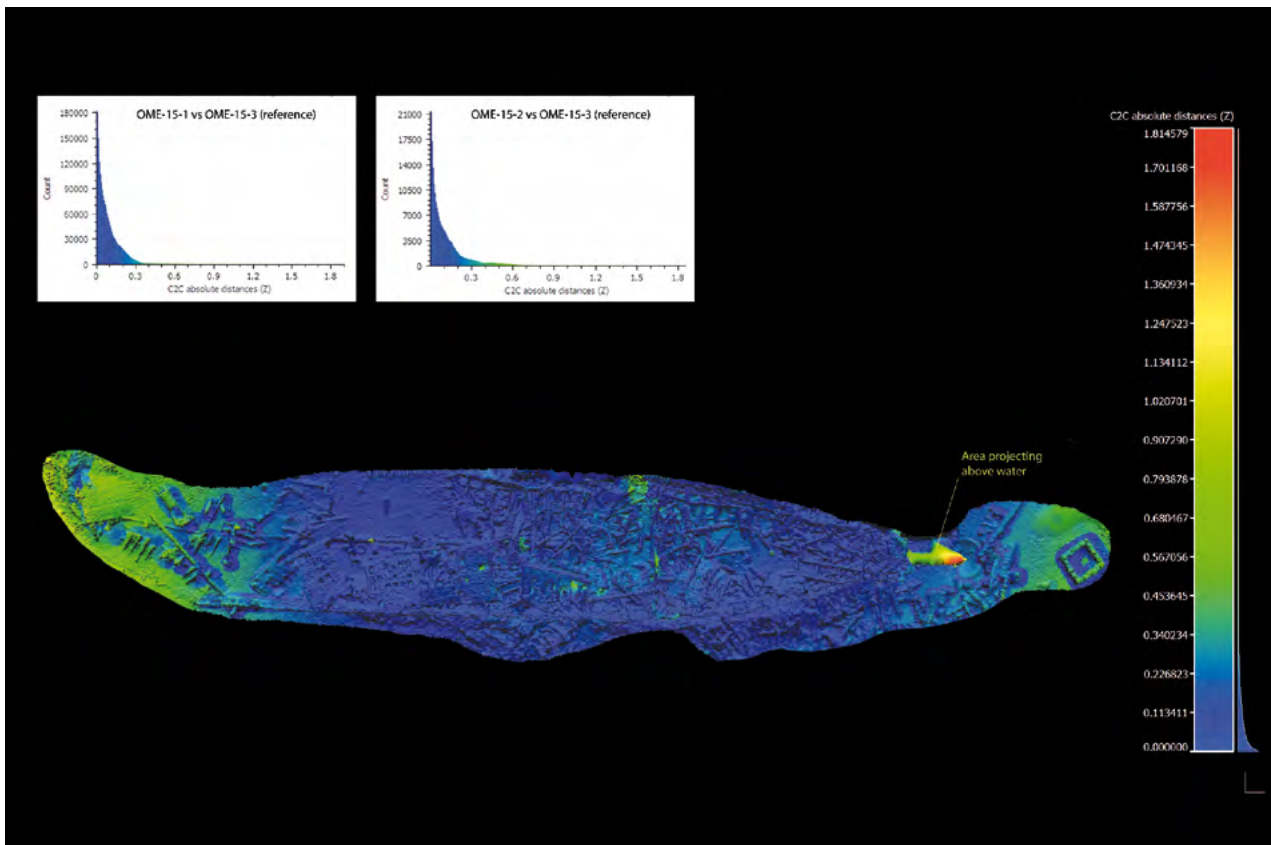


Figure 11. Comparison of 3D data captured for SS *Omeo* during recording run OME-15-2 against reference data from run OME-15-3. The maximum deviation is approximately +0.9 m in elevation (excluding areas projecting above water).

Implementation

The training workshops marked an important milestone in the life of 3DMAPPR in that they represented an informal transition from testing and evaluation to roll-out and implementation by the wider MAAWA membership. As part of this transition, the 3DMAPPR team has continued to provide advice and support to MAAWA members either planning or actively engaged in 3DMIP documentation projects. Indeed, since the completion of the workshops, MAAWA members have demonstrated considerable initiative, having employed 3DMIP to record several additional maritime archaeological sites in and around the Perth region, including *Petrel*, *Gay Dragon* and the *North Mole Barge*. It is hoped that future recording projects will be formalised through the creation of a number of working groups, each of which will be tasked with the ongoing documentation of a particular site or sites. These groups could additionally serve to enhance capacity-building within the MAAWA membership by providing an informal setting in which skills and experience can be disseminated.

The 3DMAPPR team has also provided training materials and technical support for two overseas projects, namely the Vietnam Maritime Archaeology Project (VMAP), and the 2015 Capacity Building in Safeguarding Underwater Cultural Heritage workshop held in Selayar and Makassar (South Sulawesi, Indonesia). These projects provided an excellent opportunity not only to deploy and refine training content developed as part of 3DMAPPR, but also to engage in a dialogue with overseas colleagues regarding the practicalities of employing low-cost 3DMIP for archaeological documentation, particularly in contexts where time, funding, and other resources may be at a premium.

Concluding remarks

The results of the present investigations highlight the potential of low-cost 3DMIP as a cost-effective, accurate and highly flexible means of enabling ‘citizen scientists’ to actively contribute to the documentation of wreck sites and other elements of maritime cultural heritage. Using consumer-grade ‘action’ cameras in tandem with a suite of open-source and commercial software, it is now possible for avocational maritime archaeologists with only a minimum of training and experience to objectively document even relatively large and complex underwater sites in a fraction of the time it would take using traditional methods—a fact clearly demonstrated in the case of *SS Omeo*. Moreover, the data generated using 3DMIP can be re-purposed to suit a variety of other uses, ranging from documentation and management, through to the creation of sophisticated visualisations and immersive virtual reality experiences. The latter in particular opens up the exciting possibility of providing people who have mobility constraints or lack appropriate dive training access to underwater cultural heritage sites. This potential to move beyond ‘pretty pictures’ (Falkingham 2014) makes low-cost 3DMIP a powerful tool for community education, outreach and research—and gives broader expression to Malraux’s (1967) concept of the *musée imaginaire* or ‘museum without walls’.

Nevertheless, while the use of low-cost 3DMIP can be seen to have broad and overlapping benefits for different sectors of the maritime archaeological community, several factors need to be acknowledged. Firstly, the technique, while robust, demands that users be aware of the limitations of both their equipment and the environment(s) in which they are working (McCarthy & Benjamin

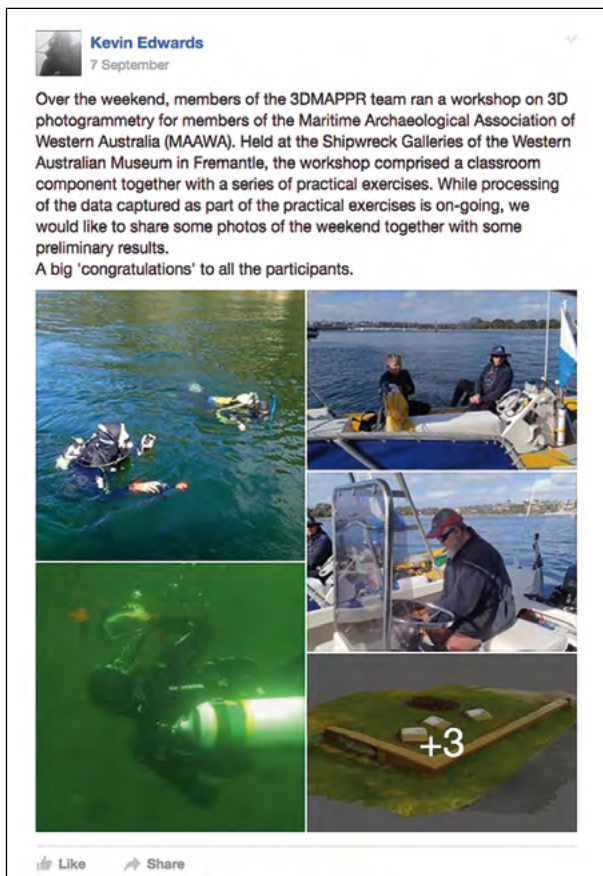


Figure 12. Screen capture of a post on the 3DMAPPR Facebook page.

2014: 112). Factors such as lighting and water quality necessarily impact on both the approach(s) taken to site documentation and subsequent processing requirements. Secondly, the overall quality and accuracy of 3D reconstructions of sites or features can be difficult to assess. While the significance of this will vary according to the intended use(s) to which the data will be put (visualisation versus erosion modelling, for example), appropriate controls and good recording practices should be implemented to minimise potential sources of error. Finally, incorporation of 3DMIP into an archaeological workflow requires

that adequate consideration be given to the issues of processing capability and long-term data management (Benne 2015; McCarthy 2014: 177). This is particularly critical considering that any given photogrammetric recording run can generate hundreds, if not thousands, of images. Taken together, these factors only serve to foreground the importance of fostering an 'open science' approach that encourages cooperation, skill-sharing, and capacity-building amongst practitioners in order to ensure successful and consistent outcomes. This is an approach that MAAWA, as part of its broader 3DMAPPR initiative, hopes to encourage.

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