PHOTOGRAMMETRY AS A TOOL FOR MONITORING SUBMERGED CULTURAL RESOURCES: THE EMERALD BAY STATE PARK WORKSHOP

MATTHEW MAUS
CENTER FOR UNDERWATER SCIENCE, INDIANA UNIVERSITY, BLOOMINGTON, IN 47405

DENISE JAFFKE
CALIFORNIA STATE PARKS, TAHOMA, CA 96142

SAMUEL HASKELL
CENTER FOR UNDERWATER SCIENCE, INDIANA UNIVERSITY, BLOOMINGTON, IN 47405

In recent years, Computer Vision photogrammetry has been demonstrated to be a feasible, powerful tool for underwater archaeological research, but relatively little has been written about photogrammetry as a tool for in situ monitoring of underwater cultural heritage. This paper presents the methodology and results from a July 2016 underwater photogrammetry workshop conducted at Emerald Bay State Park at Lake Tahoe, involving resource managers and researchers from California State Parks, Indiana University, and the University of Southern California. The application of photogrammetry as an accessible, comprehensive, and cost-effective tool for regular site-level monitoring to inform resource management and support public stewardship is discussed.

With the advent of increasingly accessible and effective photogrammetry, Computer Vision is quickly entering the mainstream of underwater archaeological research design. While this development is beneficial to all aspects of archaeological investigation and interpretation, the potential for photogrammetry to expand and improve the monitoring and stewardship of submerged cultural resources also merits consideration.

In July 2016, California State Parks, Indiana University (IU), and the University of Southern California collaborated on an underwater photogrammetry workshop at Emerald Bay State Park, Lake Tahoe, California. The objectives of this workshop were to train participants in underwater photogrammetry techniques, to demonstrate underwater photogrammetry as a feasible tool for routine monitoring of submerged cultural resources, and to establish new monitoring baselines for submerged cultural resources in the park as part of efforts to create California’s first Maritime Heritage Trail (Jaffke and Dodds 2016). Workshop participants recorded multiple submerged historic watercraft in park waters after initial instruction by IU faculty in techniques for rapid underwater image acquisition and photogrammetric processing. The methodology and results from four sunken vessels recorded during the project are presented here.

With currently available technology, underwater photogrammetry is an accessible and cost-effective tool for the routine acquisition and analysis of accurate and comprehensive data to monitor submerged cultural resources. In effect, Computer Vision photogrammetry makes it possible for resource managers to monitor more submerged cultural sites and make more informed management decisions about those sites. Additionally, photogrammetric monitoring data may also support public outreach efforts by providing ready-made 3D models for digital interpretation of sites. Finally, the techniques described in this paper are sufficiently accessible to offer the diving public the opportunity to assist resource managers with imagery acquisition for 3D modeling, thereby potentially improving monitoring while also sharing the spirit of stewardship with stakeholders. This further supports stewardship, as effective management is buoyed through education of the diving and non-diving public (Cohn and Dennis 2011).
BACKGROUND

Photogrammetry and Underwater Archaeology

“Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena” (American Society for Photogrammetry and Remote Sensing 2016). Since the earliest formative period of the field, adapting photogrammetry for underwater use has been a goal of maritime archaeologists seeking to efficiently and accurately record archaeological sites within the constraints imposed by working in submerged environments (Bass 1966, 2006; Drap 2012; Drap et al. 2013; Van Damme 2015b; Yamafune et al. 2016). The earliest example of archaeological underwater photogrammetry was conducted in Yassi Ada, Turkey in 1963-64. Although it was a successful demonstration, the photogrammetry project at Yassi Ada was expensive, technically complex, and labor-intensive (Bass 1966). Despite ongoing experimentation since then, widespread adoption of photogrammetry was long delayed as a tool for underwater site recordation as the potential benefits did not outweigh the drawbacks as compared to conventional direct-diver survey (Van Damme 2015a, 2015b).

However, as a result of converging technological improvements in software, computer processing, and digital cameras, photogrammetry has rapidly developed as an increasingly feasible and powerful tool for detailed and cost-effective underwater archaeological recordation (Bass 2006; Van Damme 2015a, 2015b; Yamafune et al. 2016). In recent years, maritime archaeologists have demonstrated underwater photogrammetry to be a flexible technique for accomplishing various research objectives, including 3D recordation of archaeological excavations and complex in situ features (Balletti et al. 2016; Costa et al. 2015; Demisticha et al. 2014; Diamanti et al. 2011; Drap et al. 2015b; McCarthy and Benjamin 2014; Skarlatos et al. 2012; Van Damme 2015b; Yamafune et al. 2016; Zhukovsky et al. 2013), generating 3D shipwreck models from archived imagery (Mertes and Gulley 2014; Van Damme 2015b), recordation of submerged architecture (Bruno et al. 2015; Henderson et al. 2013; Mahon et al. 2011), photogrammetry surveys in low-visibility water (Maus and Haskell 2016; McCarthy and Benjamin 2014; Van Damme 2015a, 2015b), and archaeological recordation utilizing Remotely Operated Vehicles (ROVs) in deep water environments (Drap et al. 2007, 2015a, 2015b; Gawlik 2014). While these projects have utilized a variety of technical workflows—such as stereovision techniques, custom hardware, and in-house software—an increasing number of archaeologists are utilizing inexpensive, off-the-shelf Computer Vision software.

Computer Vision Photogrammetry

Computer Vision photogrammetry is distinct from conventional photogrammetric methods, in that the technology results from the development of automated systems for interpretation of the visual world as a part of Artificial Intelligence research rather than cartography. Most leading Computer Vision systems are characterized by Structure-from-Motion (SfM) imaging techniques that utilize feature-detection algorithms to automatically match and align overlapping multi-image datasets. Features matched in three or more images are located in a 3D coordinate system according to the principal of intersecting rays, in the process determining camera location and generating a sparse point cloud. After image alignment, additional features may be detected more efficiently by utilizing the known locations and orientations of the images in order to generate a dense point cloud. By interpolating between points to create polygons, a 3D mesh is created. After completion of the SfM process, the model may be further enhanced by generating a texture from the imagery and draping it over the mesh (Van Damme 2015b:4-16).

Over the past decade, Computer Vision photogrammetry software has become widely available across a broad range of open-source and commercial packages. While users should be cautious using the automated algorithms hidden within “black box” software packages (Remondino et al. 2012), systematic tests indicate that contemporary Computer Vision models are comparable to those produced with terrestrial laser scanners, and are sufficiently accurate for cultural heritage documentation (Doneus et al. 2011; Koutsoudis et al. 2013). Furthermore, McCarthy and Benjamin (2014) and Mertes et al. (2014)
found that photogrammetric measurements of models created using Agisoft Photoscan—a popular SfM software package also used in this study—were accurate when compared to conventional measurements collected by divers. However, in both studies, shorter measurements were found to be less consistent, possibly as a result of diver error during conventional recording. Using currently available technology, it is now feasible to create accurate and detailed 3D models of submerged cultural resources using relatively inexpensive camera systems and accessible off-the-shelf photogrammetry software (McCarthy and Benjamin 2014), with results sufficient for in situ monitoring purposes and often superior to conventional direct-diver survey and photography in terms of quality and cost.

**Underwater Photogrammetry as a Monitoring Tool**

Despite the recent proliferation of photogrammetry in the field of underwater archaeology, relatively limited reference has been made in the literature to the use of photogrammetry as a part of site assessment and monitoring (e.g. Henderson et al. 2013; Van Damme 2015b; Yamafune et al. 2016), with the vast majority of current publications focusing on the application of photogrammetry to accomplish research objectives. While McCarthy’s (2014) discussion of the merits of photogrammetry as a tool of great potential in contract-led terrestrial archaeology is a notable exception to this trend, the application of photogrammetry as a routine monitoring tool for informing management of underwater cultural heritage has not been emphasized.

Considering the prevalence of submerged cultural resources across the globe and the limited means available to the few professionals tasked with managing these resources, this is more than just an academic point. For instance, within the California State Parks system—where this study took place—there are over 12,000 recorded cultural resources, but only 10 submerged sites have been catalogued to date (Dodds and Jaffke 2015). Far from demonstrating a lack of underwater cultural heritage, this number belies a much greater extent of submerged cultural resources under California State Parks jurisdiction as additional sites are inferred from historical sources or are known informally but have not been sufficiently recorded due to the generally slow development of underwater archaeology in California (Foster 2016).

Moreover, submerged site formation is recognized to be a dynamic product of a suite of cultural and natural processes from the time of initial deposition to the present day (Gibbs 2006; Martin 2011; Muckelroy 1978), including natural degradation, environmental scrambling, unintentional diver damage, salvage, and other relevant phenomena. Tracking changes caused by these processes is fundamental to determining effective policies to counteract resource degradation where possible. Thus, underwater photogrammetry holds great potential to decrease the logistical burdens of site monitoring while providing high quality data to guide policy and preservation.

Building on McCarthy and Benjamin’s (2014) “accessible, diver-based approach” to underwater photogrammetry, this paper describes the application of underwater photogrammetry as a cost-effective and accessible methodology for in situ monitoring of submerged cultural sites to inform management decisions and support public outreach. By utilizing a simplified image acquisition methodology, divers may collect sufficient data to generate detailed models that are accurately scaled and oriented. Site-level models provide a comprehensive record regardless of the familiarity of the diver with the site, and may be compared with earlier models or other site records to track changes. The methodology and results from the July 2016 Underwater Photogrammetry Training Workshop at Emerald Bay State Park are presented as a demonstrative case study.

**EMERALD BAY STATE PARK**

**Emerald Bay Historical Background**

Lake Tahoe's crystal waters have attracted people for generations, but it wasn't until the 1850s that the region had its first year-round settlers when logging camps formed around the basin in order to supply the lumber required to build the Comstock silver mines. Knowing that logging was a fleeting
industry, the camp owners quickly turned to tourism. By 1900, Tahoe's summer resorts were catering to visitors from the nearby Nevada cities and the larger California cities to the west. Tahoe was truly a summer playground, with recreation at the resorts focused around boating and other water activities.

During the early twentieth century, as the Tahoe Basin attracted more interest and more tourists, diverse resorts appeared along the shores of the lake. Growing numbers of eastern visitors joined members of San Francisco's elite and wealthy mining and business interests of the Comstock at the lake's best hotels. People of more modest means camped or vacationed in rustic hotels, cottages, and camps. Dr. Paul and Mrs. Lucy Kirby built the first summer resort in Emerald Bay near where the historic Vikingsholm estate is now located at the southwest end at the mouth of Eagle Creek in 1884. The early resort consisted of a hotel, cottages, tents, and a steamer landing, and continued operation until 1892 (Nesbitt 1989:8). Fifteen years later, Russell and Margaret Graves began construction of Emerald Bay Resort/Camp, located on the northwest shore of Emerald Bay. The new resort offered cottages, tents, a butcher shop, an express depot, a post office, a dance pavilion, and a steamer landing for the S.S. Tahoe, "Queen of the Lake" (Nesbitt et al. 1990:59-75).

Nelson Salter purchased the resort in 1914, continued to make improvements, and launched a promotional campaign that brought people to Emerald Bay from all over the nation. Guests had their choice of several activities while vacationing at the resort, including bathing, fishing, mountain climbing, plane rides, movies, bingo, campfires, dancing, tennis, horseback riding, picnics, and croquet (Marx and Lawrence 2004). Salter also operated a 40-foot launch equipped with a 20-horsepower engine and electric lighting for excursions around the lake, day and night (Foster et al. 2016). The bay offered calm waters, and the fleet of small boats the resort offered to guests was undoubtedly the most popular form of recreation.

Emerald Bay State Park hosts an extensive collection of submerged historic shipwrecks associated with this history of recreational land and water use, including two abandoned barges and at least 11 small recreational watercraft associated with the Emerald Bay Resort, collectively termed the “Mini-Fleet” (Figure 1). These cultural resources exhibit unique vernacular construction materials and techniques, date to the late-nineteenth through the mid-twentieth centuries, and are well preserved in the cold, fresh water of Lake Tahoe (Foster et al. 2016, Jaffke 2012; Marx and Lawrence 2004; Smith 1991, 2005). As one of the earliest underwater archaeological preserves in California with over 20 years of monitoring data collected by direct-diver survey and photography (Dodds and Jaffke 2015; Jaffke 2012; Smith 1991, 2005) as well as the proposed establishment of California’s first Maritime Heritage Trail in park waters (Jaffke and Dodds 2016), Emerald Bay State Park was selected as the ideal location to conduct the workshop.

Sites Recorded During the Emerald Bay State Park Workshop

Models were produced of four sites photographed during the workshop, including two sunken recreational watercraft of the Emerald Bay Mini-Fleet—a Hard Chine Fishing Boat (CA-EB-MF4) and a Lapstrake Motorboat (CA EB MF5)–near the boat camp in the north, and Barges I and II (CA-EB-B1 and CA-EB-B2) resting adjacent to each other alongside the southern shore of the bay. Each of these sites is open to the recreational diving public, and the barges are enhanced with a mooring buoy and an underwater interpretive monument.

CA-EB-MF4, resting in 13 meters of water, exhibits simple hard chine construction with a flat bottom and overall length of just under 16 feet (4.9 m). A pair of oarlocks mounted on the gunwales and a perforated live well are centrally located (Figure 2). When first recorded, the hull was reinforced with a thwart mounted just aft of the live well that doubled as a seat, as well as a smaller pilot’s seat in the aft starboard corner held up by a small board that also provided lateral reinforcement (Figure 3). Both the thwart and the pilot’s seat have since become disarticulated but remain within the sunken boat. Finally, a ceramic drain pipe—possibly used to hold fishing rods—rests along the starboard hull next to the pilot’s seat (Smith 2005).
Figure 1. A boat typical of the Mini-Fleet recreational watercraft in use in Emerald Bay c.1931-1945. Photograph courtesy of California State Parks Photographic Archives (object number: 090-26286).

Figure 2. Hard Chine Fishing Boat (CA-EB-MF4) orthomosaic.
CA-EB-MF5, in 12 meters of water, is a 15 foot-long (4.6 m) motorboat exhibiting lapstrake construction supported internally by ribs and stringers, a plumb stem, and a reinforced mount for an inboard engine (Figure 4). The rear of the boat is covered, but has cutouts for the tiller and rudder. Two portholes in the transom—one now covered with a metal patch—likely served as an exhaust port and access for the propeller shaft. In comparison with the rest of the Mini-Fleet watercraft, CA-EB-MF5 exhibits greater structural complexity and stability, likely intended to resist the vibrations produced by one-cylinder engine operation. Finally, judging by the lack of machinery and the placement of several rocks still in situ in the base of the vessel, it is likely that CA-EB-MF5 was intentionally sunk and abandoned historically (Foster et al. 2016; Smith 2005). Both CA-EB-MF4 and CA-EB-MF5 are mostly intact, with green and white paint still visible on the exterior hull.

Two historic barges constructed of massive ponderosa pine timbers are three to 12 meters deep near the southern shore of Emerald Bay. Barge I, with a remaining length of 85 feet (25.9 m), lies perpendicular to the shore with its northwestern hull end protruding out of the water during low water years. The hull appears to have grounded atop boulders, and wave action has since worked the hull apart (Figure 5). Twenty-nine of the frames, 16 hull strakes, and the eastern transom remain attached to the northern hull side (Smith 1991). The western transom and a majority of the southern hull side are disarticulated. Only one bulkhead and one bitt remain in place. There appears to have been an attempt to salvage portions of the hull, since several of the longitudinal bulkheads are neatly piled on the submerged slope just north of Barge I. Barge II parallels the shoreline approximately five meters south of Barge I (Figures 6 and 7). Within the 106 foot-long (32.3 m) barge there are 55 single timber frames spanning the hull (Smith 1991). Natural deterioration has begun in the bulkheads at the southern end of the barge, and historical salvage attempts succeeded in removing approximately 75% of the decking. However, hull integrity is otherwise almost totally intact.
Figure 4. Lapstrake Motorboat (CA-EB-MF5) orthomosaic.
Figure 5. Barge I orthomosaic.

Figure 6. Barge II orthomosaic.
DATA COLLECTION

Site Preparation

In order to make photogrammetric recordation feasible as part of a routine rapid assessment protocol, the methodology employed in the Emerald Bay workshop was designed to accomplish site preparation and image acquisition during a single dive. Furthermore, while recording depths were fairly shallow (13 meters or shallower), the more severe pressure gradient experienced while diving at altitude (1,905 meters) and the low water temperature (64° F at surface, 45° F under 5 m) reduced the limits of safe bottom time. Within these constraints, rapid image acquisition was especially important to safely and efficiently record each site.

Typically, this technique is best accomplished with a team of two or more divers, both for safety purposes and to carry the cameras and other equipment on a single descent. First, workshop participants received classroom instruction in site preparation, image acquisition, and processing techniques. Then, following observation of an underwater demonstration of the data collection process on the Lapstrake Motorboat, participants applied their training while acquiring imagery of multiple sites in Emerald Bay State Park. Some of the imagery collected during this training was used to generate the models included in this report.
Prior to image acquisition, divers deployed two or more coded target (CT) panels and conventional photographic scale bars throughout each target area. The panels were fabricated by adhering a 12-bit coded target printed on a Mylar sheet to an 11” x 8.5” polyethylene cutting board weighted for negative buoyancy by fastening a steel strap to the back side. Additionally, a CT scale bar was fabricated by fastening two CT panels to an aluminum rod with the distance between the centers of each CT measuring exactly one meter (Figure 8). A compass was also attached to the CT scale bar rod to facilitate model orientation. The coded targets were printed using Agisoft Photoscan, with each providing a unique true point for software reference.

Site preparation served the following purposes:

1. By providing known distances, CTs and photo bars facilitate the establishment of scale in the final model, which is necessary for measuring distance, area, and volume. Furthermore, multiple sources of scale allow estimation of error by comparing known distances throughout the model.

2. Used with an underwater compass, photo bars or CT scale bars (as described above) may be deployed in such a way as to indicate cardinal directions in the final model. This is an expedient method for orienting models of submerged sites to north.

3. CTs assist with image alignment by providing unique true points of reference that Agisoft Photoscan automatically detects, or that may be placed manually by the user. Additionally, while often unnecessary for successful model generation, image alignment rates may be increased by placing large numbers of CTs around the site, as described by Yamafune et al. (2016).

4. CTs assist with alignment of separate but contiguous target areas, or “chunks”–as termed by Agisoft–in the photogrammetric processing stage. When documenting larger sites, CTs may be placed along the boundaries of these processing chunks. This has the added benefit of simplifying image acquisition by breaking the site into more manageable pieces and allowing more than one diver to simultaneously collect imagery of a site without excessive overlap or diver intrusion into the imagery.

Additionally, chunks aid in post-processing by reducing computer resource demands, as images processed within a chunk must be compared only with others in the same chunk, rather than with all images within the dataset of the entire site (Agisoft LLC 2016:66). Chunk processing was utilized to generate the models of the barges, but is not necessary for smaller sites and therefore was not used to record the recreational watercraft. Chunks may alternatively be aligned using images shared by both chunks or by computing an estimated best fit of the point clouds of adjacent chunks. Finally, photo bars or other known distances may be substituted for CTs in order to establish scale, estimate error, and orient the final model to north. While usually more accurate than other sources of scale, CTs are not necessary if their benefits are determined to be unimportant for specific project goals.

**Image Acquisition**

After site preparation, divers collected imagery of the target areas. The underwater recordation process is simplified by Photoscan, as camera pre-calibration is not required (Agisoft LLC 2016). In order to align the images and build three-dimensional models, Photoscan requires the camera to change position between images with a minimum of 60% side overlap and 80% forward overlap for each image relative to the adjacent images (Agisoft LLC 2016). Divers accomplished this by slowly swimming closely-spaced parallel transects while taking top-down photos at an interval of one or two images per second using the time-lapse function on GoPro Hero 4 cameras (Figure 9). Where divers encountered significant relief, such as vessel sidewalls, oblique photographs were similarly recorded to resolve vertical surfaces and structural detail. Furthermore, divers were careful to record a buffer area around the areas of interest, as model quality degrades at the edges of image alignment. During processing in Photoscan, this may be resolved without impacting the desired model by simply excluding the buffer area outside of the bounding box or by cropping the edges of the buffer area after processing the model.
Figure 8. One-meter CT scale bar (foreground) and CT panel (background) deployed on Barge II.
While conducting underwater photo transects, distance-to-target is limited by visibility and water depth, and must be balanced with the desired detail in the final model, the size of the target area to be recorded, and computer resources available for processing. In short, images acquired closer to the target, or near-target images, may produce more detailed models, but a narrower swath width necessitates the acquisition and processing of more imagery. On the other hand, far-target images efficiently record larger areas and are therefore much easier to align, but do not capture as much surface detail. In order to achieve optimal results, divers conducted both near- and far-target transects, as it is possible to pair images from multiple distances and perspectives. Of the sites reported here, all were at least three meters deep, with an estimated visibility ranging from seven to 10 meters. Divers averaged between 1.19 and 1.93 meters distance-to-target during image acquisition.

PHOTOGRAMMETRIC PROCESSING

Summary Workflow

Following photographic recordation, all images were reviewed manually and low quality images were removed. The remaining images were bulk pre-processed using Adobe Lightroom to correct white balance and enhance contrast, clarity, and sharpness. This step is intended to improve image alignment and the quality of the final models, textures, and orthomosaics generated by photogrammetric processing. Images should not be cropped, rotated, or corrected for lens distortion, as Photoscan compares images to
calibrate for distortion and therefore any modification of image geometry is not recommended (Agisoft LLC 2016).

The photogrammetry software used in this study was Agisoft Photoscan Professional 64-bit v1.2.6, an SfM package that has consistently performed strongly in systematic tests (Doneus et al. 2011; Koutsoudis et al. 2013; McCarthy and Benjamin 2014; Mertes et al. 2014). While numerous other photogrammetry packages have become available in recent years, Photoscan is increasingly the software of choice used by maritime archaeologists (Costa et al. 2015; McCarthy 2014; McCarthy and Benjamin 2014; Mertes et al. 2014; Torres 2015; Van Damme 2015a, 2015b; Yamafune et al. 2016; Zhukovsky et al. 2013). The Photoscan workflow is relatively automated with a straightforward interface. While this means that a novice user may effectively produce high quality models, Photoscan also includes many advanced tools that permit an expert user to further improve processing and data analysis results. In the interests of brevity, only a basic summary workflow is presented here.

First, after importing the image datasets, coded targets may be detected automatically or manually identified in the images to assist with image alignment. Next, photogrammetric processing begins with the image alignment stage, wherein images are analyzed using a feature detection algorithm and compared with other images in the dataset to find matches. During this stage, Photoscan also calculates image geometry, both from photographic metadata and comparative analysis of the image dataset. Overlapping images with three or more matching features are then aligned according to the principal of intersecting rays to determine their relative location and orientation within a 3D volume, generating a sparse point cloud from the matching features in the process. Chunks may be aligned at any time after image alignment (Agisoft LLC 2016).

At this point, inspection of the sparse point cloud is recommended to assess whether or not image alignment has been successful. For this reason, it makes sense to process the imagery on a low setting in the field to test if the dataset is sufficient for further processing. If image alignment is determined to be unacceptable, researchers may refine their dataset or processing settings, or simply attempt image acquisition again. Otherwise, the imagery should be reprocessed at a higher setting after the conclusion of fieldwork in order to produce an improved model. Once image alignment is determined to have been successful, the next step is to generate a dense point cloud, which calculates depth information using camera positions estimated during image alignment. This results in a highly detailed, dense point cloud of the subject area, which may be similar as dense as point clouds built by LIDAR (Agisoft LLC 2016). Dense point cloud generation is the most computer resource intensive step, and may take hours or days to complete depending on the imagery dataset, computer system, and processing settings. The final stages involve the generation of a 3D mesh from the dense point cloud and, finally, a texture is created from the rectified imagery and draped over the mesh. After model completion, reference points and scale bars—which may be any known distance—should be established throughout the modelled site. This allows estimation of scalar error as well as measurement of distance, area, and volume. Additional products may be generated such as processing reports, tiled models, Digital Elevation Models (DEMs), and orthomosaics; the latter providing a highly detailed, rectified image of the site that is analogous to, but often more detailed and accurate than, a traditional site plan (Agisoft LLC 2016).

Finally, the completed models may be uploaded to online platforms to facilitate researcher and public access via the internet. Accordingly, the four models produced in the Emerald Bay workshop were uploaded to Sketchfab.com, which is a “leading platform to publish and find 3D and VR content” (Sketchfab 2016). Using this medium, the four models in this report may be viewed in 3D via an internet browser. Additionally, the online models of the Lapstrake Motorboat and Hard Chine Fishing Boat were further enhanced with 3D guided tours that included interpretive text (Figure 10).

Results

Following the workflow above, 3D models and orthomosaics were generated for the Hard Chine
Fishing Boat, Lapstrake Motorboat, and Barges I and II. Model areas ranged from 16 to over 500 square meters, with corresponding differences in the size of the imagery dataset (Table 1). While the Mini-Fleet watercraft represent small sites, the barge models demonstrate that this technique is also valid for larger shipwrecks, facilitating much faster and more detailed data collection than by conventional means. The imagery for each model was collected on a single dive in good visibility, with multiple divers collecting imagery of the barges simultaneously. Lower visibility conditions would require more imagery to achieve acceptable coverage of the target areas, and therefore would necessitate more image acquisition and processing resources.

Comparison of model measurements made in Photoscan against 15 manual measurements from the initial site records shows there is little discrepancy (Figure 11). While the period of time between the manual and photogrammetric measurements is significant—25 years in the case of the barges—the average percent agreement between the model and control measurements is 95.50%. This attests to the general stability of the four sites over this time period, as well as the fidelity of photogrammetric recordation to the environment and the accuracy of the researchers who collected the initial conventional measurements. Interestingly, longer photogrammetric measurements appear to be more consistent than shorter measurements relative to the model size as a whole. For instance, measurements over four meters in length averaged 98.85% agreement, whereas shorter measurements averaged only 91.68% agreement. This is consistent with similar tests conducted by other maritime archaeologists (McCarthy and Benjamin 2014; Mertes et al. 2014). The greater accuracy of longer measurements in comparison to shorter measurements is further highlighted by the total root mean square error (0.11304) for all measurements ranging in length from 0.25 to 32.36 meters. This pattern most likely scales with model size. Therefore, a detailed model of a small feature could be expected to return accurate measurements of distances that are much shorter in absolute terms, but long in relation to the overall model. More systematic testing may be
Table 1. Photogrammetric model metadata.

<table>
<thead>
<tr>
<th>Model</th>
<th>Aligned Images</th>
<th>Average Distance-to-Target</th>
<th>Model Area</th>
<th>Estimated Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barge I</td>
<td>2089</td>
<td>1.77 m</td>
<td>284 m²</td>
<td>0.1664 cm</td>
</tr>
<tr>
<td>Barge II</td>
<td>2636</td>
<td>1.93 m</td>
<td>507 m²</td>
<td>0.3472 cm</td>
</tr>
<tr>
<td>Hard Chine Fishing Boat</td>
<td>705</td>
<td>1.19 m</td>
<td>16.2 m²</td>
<td>0.1588 cm</td>
</tr>
<tr>
<td>Lapstrake Motorboat</td>
<td>363</td>
<td>1.65 m</td>
<td>16.7 m²</td>
<td>0.0979 cm</td>
</tr>
</tbody>
</table>

Figure 11. Accuracy assessment comparing photogrammetric (model) measurements with manual measurements from the initial site records (control).

necessary to clarify this inference. Finally, the estimated error for all four models–calculated by comparison of the discrepancies of internal distances within the 3D models–ranges from 0.0979 cm to 0.3472 cm.

While overall model generation was successful, some modular errors are visible in the final products. In most cases, these appear to be the result of insufficient image overlap, object self-occlusion, or extreme variations in brightness inhibiting localized image alignment – such as the north-facing sidewall of Barge II, which was both backlit by direct sunlight and obscured in shadow during image acquisition. Unfortunately, it can be difficult to correct modelling errors, as Photoscan–like most other Computer Vision software packages–is a “black box” (Remondino 2012), and the cause of some errors is therefore not always apparent. However, visual inspection of the models and comparison with the unprocessed imagery is usually sufficient to judge the basic fidelity of the final product to the actual scene as significant errors are often obvious. In the case of unresolvable errors, it may be best to attempt image acquisition again, as the problem may be inherent to the dataset. If this is not possible, any analysis in areas with errors should be avoided, or the model may have to be discarded altogether. While there is no
such thing as a perfect model, models generated using the techniques outlined here are—in our experience—reliably successful, and are usually more than sufficiently accurate and detailed for baseline establishment and monitoring purposes as well as most other research objectives.

Comparison of the results to previous monitoring data, including imagery and line drawings, indicates that there was minimal change to the Lapstrake Motorboat, Barge I, and Barge II since the start of monitoring in 1994 and 1995. However, comparison of the initial site plan with the photogrammetric model of the Hard Chine Fishing Boat indicates multiple changes since 2003: (1) the front quarter of the starboard gunwale is absent and appears to have been pulled out, (2) the thwart is disarticulated and lying just forward of the live well, (3) the ceramic pipe has been knocked over, and (4) the pilot’s seat is disarticulated and resting below its previous position (Figure 12). Furthermore, monitoring photos from 2005 show the ceramic pipe and pilot’s seat in their original location, whereas the thwart is disarticulated (and lying to the rear of the live well) and the damage to the forward starboard gunwale is already present, indicating that the damage occurred in two or more events between 2003 and 2016. While diver damage is a possible cause, anchor damage is more likely. This is because the Hard Chine Fishing Boat lies within the mooring field for the Emerald Bay State Park Boat Camp, and the damage visible in the 2016 model consists entirely of the disarticulation of hull components that would present snagging hazards for anchors, while no artifacts were removed from the site. It is unlikely that a diver would intentionally dismantle a shipwreck without removing any artifacts. Based on this information, park managers are considering options to either improve enforcement of mooring restrictions in Emerald Bay, especially around these sensitive sites, or to possibly relocate threatened vessels farther north, outside of the modern mooring field but within the Emerald Bay Resort historic district.

The Hard Chine Fishing Boat monitoring results are all the more significant because the divers who acquired the imagery were workshop participants with minimal prior background knowledge of this specific site or photogrammetric techniques. By applying techniques described here, they were able to comprehensively record the site on a single dive, and the data was then processed and analyzed in comparison with earlier monitoring data at leisure. Underwater photogrammetry made it possible to track detailed changes to the site without having to anticipate those changes and guide specific data collection objectives accordingly.

DISCUSSION

As this case study demonstrates, Computer Vision photogrammetry is an effective tool for comprehensive monitoring of submerged cultural sites. Indeed, IU researchers have been using photogrammetry as a primary recordation and analysis tool for assessments of submerged sites in the Dominican Republic, Florida, and Lake Michigan since 2015 (IU Center for Underwater Science 2015, 2016; Maus et al. 2015; Maus and Haskell 2016). The methodology employed at Emerald Bay was derived from lessons learned in these ongoing experiments.

Photogrammetry is feasible as part of a routine rapid assessment protocol. Imagery may be acquired in as little as one dive, permitting regular assessment of more sites due to reduced logistical burdens. Additionally, photogrammetric models and orthomosaics are typically more accurate and detailed than is possible by manual recordation. In fact, models often provide a ready-made product of sufficient quality for public outreach that may be posted online via free or inexpensive services such as Sketchfab. This improves public access to sites that are physically visited by a relatively small portion of the total public, allowing both guided interpretation and total freedom of virtual exploration for non-diving viewers that was previously impossible. In this way, monitoring data may double as outreach materials.

What’s more, as photogrammetry indiscriminately records the visible entirety of a target area, it is both more comprehensive and more objective than diver-recorded data. Granted, such conventional methods will always have their place in the archaeologist’s toolbox, and some subjectivity remains in the
Figure 12. Comparison of Hard Chine Fishing Boat (CA-EB-MF4) monitoring data from 2003 to 2016. Images are, from left to right, the 2003 line drawing included in the site record (Smith 2005), a 2005 monitoring photograph, and the 2016 orthomosaic. Observed changes are indicated by arrows and numbers: 1) forward starboard gunwale, 2) thwart / bench, 3) ceramic drain pipe, and 4) pilot’s seat.

The photogrammetric process as one must select features and sites to record based on their significance, sensitivity, or other characteristics. However, by modelling entire features and sites, photogrammetry mitigates potential subjective data filtration by the recorder and presents a more complete picture of the area of interest. This is exemplified by the Hard Chine Fishing Boat, for which it was possible to detect long term changes to the site by comparing previous monitoring data to a comprehensive photogrammetric model generated from imagery collected by researchers whose only dive objective was to systematically record the entire site. This further highlights the possibility of expanded monitoring.
through citizen-scientist programs, as volunteer divers could collect data sufficient for photogrammetric monitoring with minimal training in image acquisition techniques.

As with any technology, Computer Vision is not without its limitations. Essentially, the photogrammetric method described here is a passive remote sensing system that is therefore reliant on ambient light to function. Excessive darkness or variations in brightness caused by shadows, turbidity, or light absorption at depth may inhibit image alignment. Conventional strobes may compound this challenge, because they cast shadows that move with changing camera position and may therefore interfere with feature detection. Other researchers have overcome this challenge by using a diffuse light to illuminate target areas (Van Damme 2015a, 2015b; Yamafune et al. 2016). Additionally, while not the case in Emerald Bay, vegetation obscuring sites may complicate resolution of target surfaces, especially if the vegetation moves between frames due to surge or current. Furthermore, photogrammetry is very computationally intensive. Depending on computer resources, it can take days to process large datasets using Photoscan. However, processing time may be significantly reduced by splitting the dataset into chunks to reduce the number of comparisons that must be made between images, or by using a powerful purpose-built computer. In any case, only a relatively small portion of total processing time typically requires direct input from the user. Finally, site inspection by trained archaeologists—including observation, traditional recording techniques, and documentary photographs of key features—will remain necessary for informed management and research. Computer Vision does not fully replace, but rather augments, conventional methods.

While this case study compared photogrammetric models with earlier management data out of necessity, long term photogrammetric monitoring offers far greater potential benefits. By regularly collecting imagery of sites, much more detailed multi-temporal comparisons between models and orthomosaics may be achieved. The sooner photogrammetric monitoring protocols are adopted, the greater the benefits. The imagery datasets themselves would add to site archives that may be processed in the future as software improves. Thus, even without a pressing need to model lower priority sites, given the ease and inexpensiveness of image acquisition it would be logical to record as many sites as possible to archive site data for future use as comparative baselines. Thus, when conducting other diver operations, resource managers and researchers should be equipped and trained for basic photogrammetric image acquisition to record targets of opportunity. Similarly, volunteer divers may be trained to augment official monitoring efforts. Altogether photogrammetry as a monitoring tool is poised to revolutionize the stewardship of submerged cultural resources.

ACKNOWLEDGEMENTS

This project was made possible by California State Parks, which provided funding, lodging, marine transport, and logistical support. In addition, the authors acknowledge the important contributions of John Foster, Charles Beeker, Ken Kramer, Mylana Haydu, Tricia Dodds, Dan Shaw, Airielle Cathers, and Lynn Dodd.

REFERENCES CITED

Agisoft LLC

American Society for Photogrammetry and Remote Sensing

Balletti, C., C. Beltrame, E. Costa, F. Guerra, and P. Vernier
Bass, George F.
1966 *Archaeology under water*. Thames and Hudson: Bristol, UK.


Bruno, F., A. Lagudi, A. Gallo, M. Muzzupappa, B. Davidde Petriaggi, and S. Passaro

Cohn, Arthur B. and Joanne M. Dennis

Costa, E., C. Beltrame, and F. Guerra

Demesticha, Stella, Dimitrios Skarlatos, and Andonis Neophytou

Diamanti, Eleni, Andreas Georgopoulos, and Fotini Vlachaki

Dodds, Tricia, and Denise Jaffke

Doneus, M., G. Verhoeven, M. Fera, C. Briese, M. Kucera, and W. Neubauer

Drap, Pierre

Drap, Pierre, Djamel Merad, Julien Seinturier, Amine Mahiddine, Daniela Peloso, Jean-Marc Boï, Luc Long, Bertrand Cheminsky, and Joaquin Garrabou

Drap, Pierre, Djamal Merad, Bilal Hijazi, Lamia Gaoua, Mohamad Motasem Nawaf, Mauro Saccone, Bertrand Chemisky, Julien Seinturier, Jean-Christophe Sourisseau, Timmy Gambin, and Filipe Castro

Drap, Pierre, Julien Seinturier, Bilal Hijazi, Djamel Djamal Merad, Jean-Marc Boi, Bertrand Chemisky, Emmanuelle Seguin, and Luc Long

Foster, John W.

Foster, John W., Charles Becker, Deborah Marx, and Sheli O. Smith

Jaffke, Denise

Jaffke, Denise, and Tricia Dodds

Gawlik, Natalia

Gibbs, Martin

Henderson, Jon, Oscar Pizarro, Matthew Johnson-Roberson, and Ian Mahon

Indiana University Center for Underwater Science


Koutsoudis, Anestis, Blaž Vidmar, and Fotis Armaoutoglou

Mahon, Ian, Oscar Pizarro, Matthew Johnson-Roberson, Ariell Friedman, Stefan B. Williams, and Jon C. Henderson
Martin, Colin

Marx, Deborah, and Matt Lawrence

Maus, Matthew J., Charles D. Beeker, Mylana Haydu, and Samuel Haskell
2015 Application of Photogrammetry for Assessment and Monitoring of the 1733 San Pedro Underwater Archaeological Preserve. Indiana University Center for Underwater Science, Bloomington, IN. Submitted to Florida Division of Historical Resources (Bureau of Archaeological Research), Florida Division of Recreation and Parks (Bureau of Natural and Cultural Resources), NOAA Florida Keys National Marine Sanctuary. Copies available from Indiana University Center for Underwater Science.

Maus, Matthew, and Samuel Haskell

McCarthy, John

McCarthy, John, and Jonathan Benjamin

Mertes, J., T. Thomsen, and J. Gulley

Muckelroy, Keith

Nesbitt, Paul E.

Nesbitt, Paul E., Nancy H. Evans, and John L. Kelly

Remondino, Fabio, Silvio Del Pizzo, Thomas P. Kersten, and Salvatore Troisi
Skarlatos, D., S. Demestiha, and S. Kiparissi

Sketchfab

Smith, Sheli O.

Torres, R.

Van Damme, Thomas
2015a Computer Vision photogrammetry for underwater archaeological site recording in a low-visibility environment. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 40(5):231-238.

Yamafune, K., R. Torres, and F. Castro

Zhukovsky, M., V. Kuznetsov, and S. Olkhovsky