3D Digital Modeling of Maritime Heritage Resources: Are Small ROVs up to the Task?

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The work reported herein was completed by Ryan Solymar in partial fulfillment of the requirements for a Professional Science Masters (PSM) degree in Environmental Science at California State University Monterey Bay (CSUMB).

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Executive Summary

My primary goal of this project was to evaluate the feasibility of creating useful 3D models of submerged maritime heritage resources, rocky reefs, or other undersea structures and habitats from video obtained by a small (15 kg), affordable ($5,000 US) ROV operating at or below the depth limits of recreational scuba.

I conducted this work in collaboration with Monterey Bay National Marine Sanctuary (MBNMS or sanctuary), which is responsible for management of, and public outreach regarding, a variety of natural and cultural resources, including a large number of shipwrecks and other maritime heritage resources (MHRs), within MBNMS boundaries. The sanctuary is a potential user of the methods described in this report.

I conducted this research at California State University Monterey Bay (CSUMB) and in the field as part of Dr. Steve Moore's research lab group, which is called the Ecosystem Electronics Lab, or "EEL." My team of undergraduate Ecosystem Electronics Lab-mates, Maggie Seida and Ethan Switzer, and I were able to assist the sanctuary through this project by: (1) evaluating whether surveys by comparatively small, low-cost ROVs would be sufficient to create useful 3D models of MHRs via Structure-from-Motion (SfM) photogrammetry and (2) evaluating the potential usefulness of these models for (a) documenting the physical condition of each site, (b) characterizing the biological communities associated with each site, and (c) creating interactive public exhibits, such as virtual-reality walk-throughs of the 3D models.

More specifically, my objectives were to: evaluate the feasibility of using a small ROV (BlueROV2 by Blue Robotics, Torrance, CA) and a GoPro Hero 4 camera to collect video for building SfM models of 1-3 MHRs, and assess the level of detail reliably documented in those models with respect to the potential applications (a-c) listed above.

We successfully created a 3D model of two sunken WWII-era amphibious tracked vehicles located one atop the other off of Lover's Point in Pacific Grove, CA using video imagery collected from a small ROV. These vehicles are an MHR known to many scuba divers as the "Mating Amtracks" dive site. The model successfully captured the three-dimensional shape, approximate size, and footprint of the wreck. When the model was optimized for high resolution we were able to confidently identify many sessile macroinvertebrates associating with it (in some cases to the species level).

One important benefit of SfM modeling for underwater archaeology applications is that the SfM software algorithm largely ignores suspended particulates, effectively peeling back the curtain of dark, murky water that often obscures these objects. In so doing, SfM makes it possible for the viewer to see the full extent of even very large objects all at once, as if viewing them through air

or crystal-clear water. I confirmed that this beneficial attribute was retained in our small-ROV-based 3D models.

SfM 3D photogrammetry is also useful in cases where documenting the subject's spatial dimensions, orientation, and relationship to surrounding objects is important. Our ROV-based model of the Mating Amtracks was able to do all of this with the exception of recording the precise dimensions of the subject. This shortcoming is easily remedied by inclusion of a reference size scale, such as dots from parallel laser beams, in at least one image.

One place where the model did not do as well as more traditional photo-quadrats or video transects was in facilitating accurate identification and quantification of invertebrate species and communities living on the structure. Although portions of our ROV-based 3D models contained sufficient detail in both shape and color to allow the identification of several invertebrate species, one could more confidently identify these and many more species from the raw video used to create the model. Nonetheless, our results suggest that this aspect of the models could be improved substantially through refined data collection techniques, including improved lighting and more consistent control over the distance between the ROV camera and the surface of the object being modeled. If sufficient resolution could be obtained, the ability to see not only what is present, but also where it is growing on the 3D structure, might facilitate the detection of spatially important patterns of invertebrate growth and distribution.

Section 1: Introduction

Monterey Bay National Marine Sanctuary (MBNMS or sanctuary) is a marine protected area off the central coast of California encompassing 6,094 square miles of ocean (Fig. 1). Management of the sanctuary ensures resource protection, provides for research and education, and facilitates recreational and commercial uses compatible with the primary goal of resource protection. The mission of MBNMS staff is to understand and protect the coastal ecosystem and cultural resources of Monterey Bay National Marine Sanctuary. A submerged cultural resources study by Smith and Hunter (2003) indicates that 463 vessel and aircraft losses occurred within the jurisdiction, or adjacent to the boundaries, of MBNMS, accounting for as much as 25% of California's overall reported ship losses. NOAA's 2008 Maritime Heritage Action Plan outlined "the need to inventory and assess submerged archaeological resources." Currently very little is known about the condition of many of the MHRs other than their assumed location, based on historical records.

To more effectively manage MHRs, MBNMS staff need to be able to document the condition of these resources, and to do so at frequent enough intervals to detect damage or other changes associated with storms, corrosion, shipworms, fishing gear, unauthorized salvage, etc. It therefore becomes essential to find rapid and inexpensive ways to collect, store, and present this data.

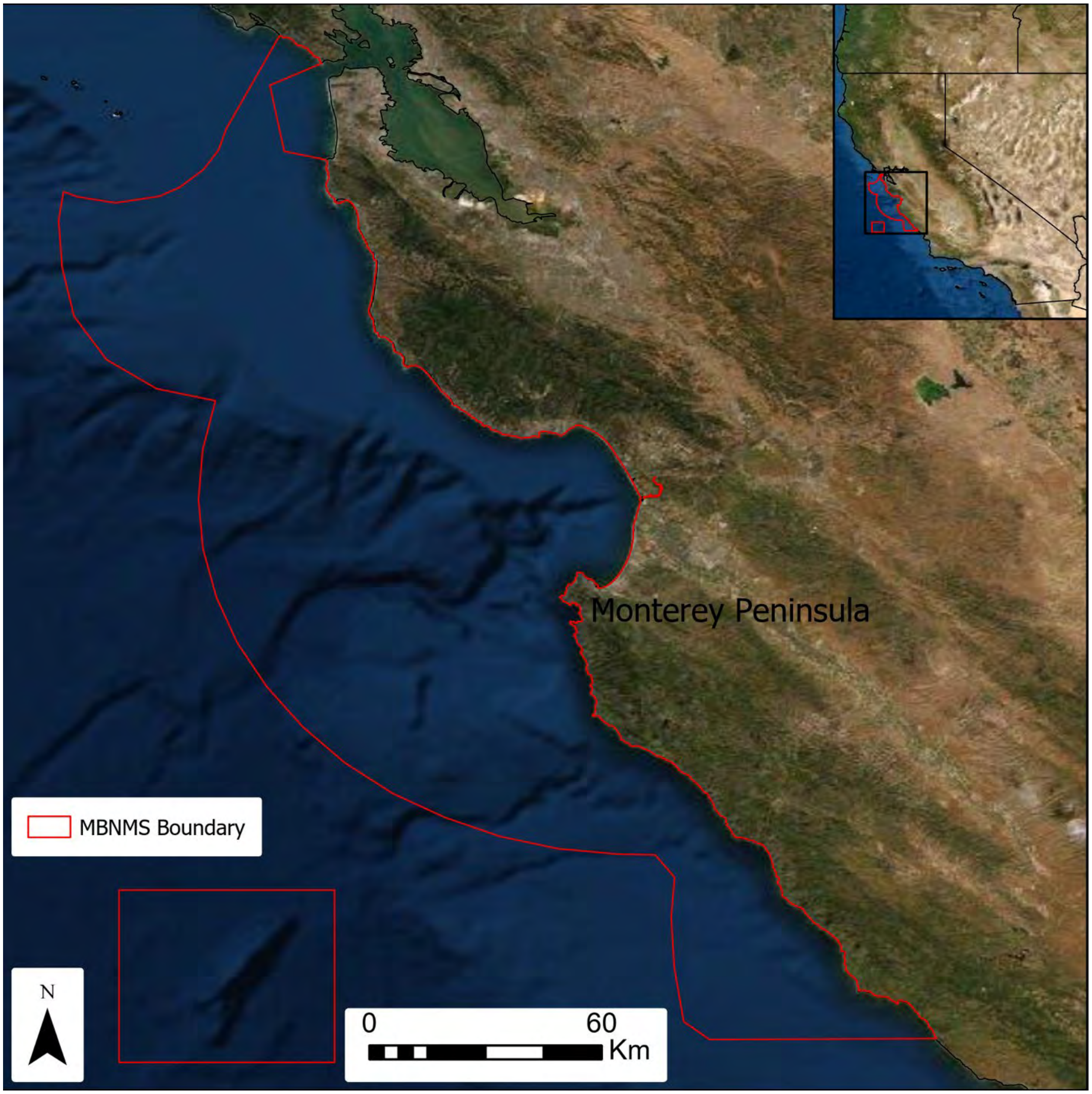

Figure 1. A map of Monterey Bay National Marine Sanctuary.

Maritime heritage resources are essentially undersea archaeological sites and can be documented in much the same way as their terrestrial counterparts for effective management and future study. For more than a decade, 3D photogrammetry via Structure-from-Motion (SfM) has been attracting the attention of teams conducting archaeological research due to its ability to rapidly and non-invasively collect and record data on monuments (Levy et al. 2014). SfM derives 3D structure from images captured by a single camera from multiple different positions (motion). This 3D structure can then be measured and analyzed digitally resulting in much less invasive study of sensitive archaeological sites.

As with terrestrial archaeology, the interest in 3D models of marine environments has increased dramatically since roughly 2010 with more than 40% of all articles in the *International Journal* *of Nautical Archaeology* mentioning the phrase "3D" or some variation of it in the years between 2016 and 2018 (McCarthy et al. 2019). The ability to rapidly collect data on archaeological sites is especially valuable when considering the logistical difficulties in accessing submerged MHRs (Flatman 2007).

There are two main paradigms for collecting underwater SfM data: diver-based surveys and ROV-based surveys. Beltrame and Costa (2018) conducted diver-based surveys coupled with SfM to effectively model shipwrecks near Sicily (less than 10m deep), and off the coast of Croatia (28m). The *Mars* project in the Swedish Baltic was carried out at a depth of 75m and required the use of rebreathers to increase safe bottom times, and the use of additional lights in the deep dark water (Eriksson and Rönnby 2017). These types of surveys often require considerable amounts of time and labor to be invested due to the limitations of SCUBA diving. For example, a Late Bronze Age ship at Uluburun required 11 years and 22,413 dives to excavate and survey, accruing significant cost and risk to the participants (Lin 2003). 3D models made via SfM using imagery collected with ROV-based surveys could significantly increase the maximum depth range possible and decrease the time, risks and costs required to complete projects like this. Deep-sea remotely operated vehicles (ROVs) have been used to construct 3D models of shipwrecks in the fjord near the German town of Kiel (Sedlazeck et al. 2009). The Black Sea Maritime Archaeology Project (external link) has even successfully used deep-sea ROVs to collect imagery to create a 3D model of the oldest complete shipwrecks discovered (Pacheco-Ruiz et al. 2018) and collected data at depths up to 2140m. In 2019 the Monterey Bay Aquarium Research Institute and E/V Nautilus successfully modeled a whale fall (external link) found at over 3000m at the Davidson Seamount in MBNMS from imagery collected with their deep-sea ROVs. These types of deep-sea ROV-based surveys require large, expensive ROVs and even larger (and more expensive) support vessels and crew. They tend to avoid working close to shore in depths less than 200 m (George Mastumoto, personal communication). This leaves a large amount of the ocean floor, particularly continental shelf areas where many wrecks occur (Smith and Hunter 2003), unexplored and insufficiently documented, because it is "too deep" for SCUBA and "too shallow" for large scale ROV operations.

The recent development of smaller and cheaper, yet highly capable, ROVs – for example, the BlueROV2 by Blue Robotics (Torrance, CA) -- may provide an easier and less expensive way for MBNMS to create SfM 3D models of MHRs at these intermediate depths. **The goal of the work described in this report was to explore and evaluate that possibility.**

It is worth noting that Sanctuary staff are also tasked with managing many of the living resources within MBNMS and with providing public outreach and education to help the public understand and appreciate their National Marine Sanctuary and its resources. SfM 3D models may be helpful with both of these efforts, as well.

Shipwrecks and other MHRs act as artificial reefs, which tend to attract and concentrate fish, sessile invertebrates, and other marine life, and they can have other profound effects on marine life and marine ecological communities (Lengkeek et al. 2013). Moreover, vessels that sink after long journeys from elsewhere can act as vectors for invasive species (Soares et al., 2020). Therefore, it would be valuable if methods used to document the condition of MHRs could also document the biological communities growing on, and otherwise associated with, those resources. It is not immediately clear whether SfM models based on small ROV surveys could do this, so **I also evaluated the ability of our small-ROV-based models to capture details of the biological communities living on these wrecks.**

In terms of public outreach and education, interactive, rotatable, 3-dimensional, digital models of MHRs are also likely to be more fun, intuitive, and engaging to explore than more traditional “flat” images or video. There is even the possibility of integrating these 3D models with virtual reality technology, so the public could “walk through” life-size virtual models of MHRs. A past study by Carrozzino and Bergamasco (2010) showed VR to be an excellent medium to inspire the public, but at that time its cost was prohibitive. Since then, technology has improved and prices have plummeted, making VR technology widely available to the general public (e.g., Oculus Rift/Quest). This added dimension, and level of immersion, may aid in inspiring ocean conservation in the public. **I did not evaluate this aspect of our 3D models in any detail, but it warrants further investigation.**

Section 2: Methods

Software Selection

Prior to the formal beginning of this project, I had experimented with 3D photogrammetry using downloadable curated image sets in three different software packages: Regard3D, 3DF Zephyr Free, and Agisoft’s Metashape. Of these 3 software packages, I found Agisoft’s Metashape most promising for the following primary reasons: Metashape allows for the highest level of user control in the model creation process; Metashape allows for the inclusion of measurements in the creation of models; Metashape allows for the use of video directly instead of having to extract still images to create models; and Metashape allows the user to upload their generated model to Sketchfab, an online free-to-use 3D model hosting platform, via an integrated publisher allowing anyone with internet access the ability to view the model.

Technique shakedown

After choosing a software package to create the 3D model, my team had to verify that we could create a model using video collected with a small ROV in the turbid water of MBNMS. To accomplish this, we mounted a GoPro Hero 4 action video camera on a BlueROV2 and carried out a series of practice dives on the mooring blocks in the east mooring field at Monterey Harbor. I was eventually able to create an accurate 3D model of two of the mooring blocks. In the process, I learned that our Ping360 scanning sonar mounted on the ROV was indispensable for reliably locating our target in limited visibility.

Site selection

After ensuring that I could reliably create 3D models, I met with Erica Burton (MBNMS Research Specialist) and Dr. Steve Moore (my CSUMB research advisor) to discuss possible MHRs to model. Ultimately, we decided on using the “Mating Amtracks” off of Lovers Point in Pacific Grove, CA (36.629780, -121.910350) as my model target site (Fig. 2).

Figure 2. A map showing location of the Mating Amtracks with Lovers Point for reference.

The "Mating Amtracks" are a pair of World War 2 era amphibious tracked vehicles (Fig. 3) that have settled atop one another on the seafloor. We chose this site for several reasons. The Mating Amtracks are easily accessible due to their proximity to the breakwater launch ramp and they have a complex, 3D structure. Although they are accessible via SCUBA (roughly 25 m deep), the Mating Amtraks are deep enough that they cannot be seen from the surface and require a fair amount of tether to be deployed (at least 1.5 times the depth depending on ocean conditions) making them a reasonable stand-in for a somewhat deeper ROV dive. Additionally, the Mating Amtracks are just deep enough that lights are required in order to resolve true color. These physical factors, coupled with their historical significance, made the Mating Amtracks a suitable site for practicing and ultimately testing/evaluating our technique.

Figure 3. This LVT-A is an amphibious tracked vehicle similar to those at the Mating Amtracks site. Note the distinctive "M-shaped" treads (red.) A drive wheel (white) is mounted on a drive shaft that passes through a large hole in the hull (purple) near the bow-end.

Data collection

My team and I collected the video required to make our models on two separate days. Our first day of data collection was February 20th 2020 and involved a crew of 3 people. The second day of data collection, after a lengthy delay due to COVID-19 restrictions, was September 2nd 2020 and was reduced to a crew of 2 people to comply with new COVID regulations. We used CSUMB's 4m Zodiac brand rigid hulled inflatable boat both days and collected our video with the EEL's GoPro Hero4 attached to our BlueROV2. The only costs accrued by the team for our two trips were gasoline for our vehicles and the boat, and parking fees.

Section 3: Results

Feasibility of developing a model

The primary goal of this project was to determine whether I could reliably create a 3D model of a submerged structure, such as an MHR, using GoPro footage collected with a small, inexpensive ROV (specifically, the BlueROV2). I found our GoPro video to be of sufficient quality to reliably create 3D models of submerged wrecks.

Model assessment part 1: Physical characteristics

The secondary goal was to evaluate the ability of the created 3D models to quickly and efficiently capture the overall structure. In 2012, the Bay Area Underwater Explorers (BAUE) conducted an extensive survey of the Mating Amtracks. Their team of 20 divers and 6 additional support staff spent "several months of planning, including a reconnaissance dive, a project meeting, two project practice days, one day of setup dives, and two days of survey and documentation dives" to create three 2-dimensional projections of one of the Amtracks (external link). Using our novel technique, my team was able to create a color 3D model (with a resolution of roughly 5 cm) of the same site in less than a day, all while staying comparatively safer and drier than would have been possible on SCUBA. I was able to accurately capture both the footprint, defined by the interface between the MHR and the sand, and the general superstructure of the wreck. In addition to capturing the basic shape, I was also able to capture distinguishing characteristics like the tread design (Fig. 4A), and through-hulls for gear shafts that were used to drive the treads (Fig. 4B). Characteristics like this can be used to help identify the potential service models of the submerged amtracks. My 3D model was also of a high enough fidelity that we would be able to determine if there were any major structural changes to the wreck, due to things like natural decay, large storms, or collision with fishing gear.

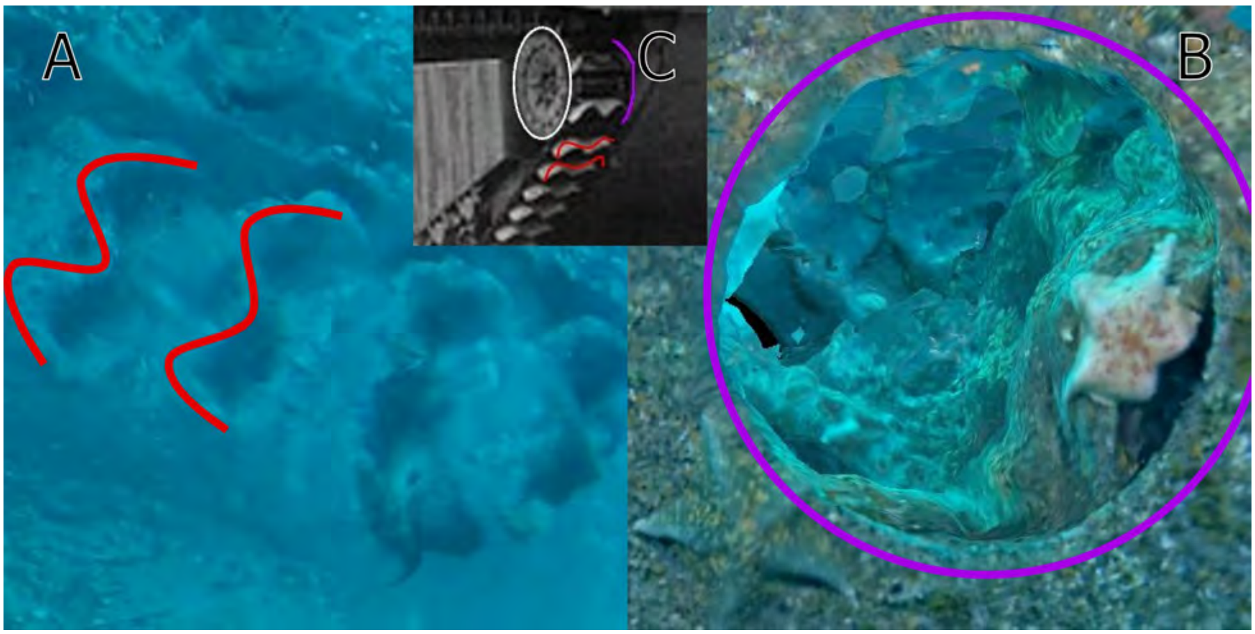

Figure 4. (A)"M-shaped" treads (red) and (B) driveshaft holes (purple) are two features that can be compared to historical imagery of amphibious tracked vehicles (C) to confidently identify the "Mating Amtracks."

Model assessment part 2: Identification of biological communities

Additionally, I wanted to evaluate whether my 3D models were of a high enough resolution to accurately identify any members of the biological communities living on the MHR. I had varying degrees of success with this. Based on my models, I seem to be able to achieve a resolution of about 1-2 cm and in some cases I was even able to resolve the "scales" and distinctive color markings on bat stars. I found that identifying macroinvertebrates is possible based on size and distinctive characteristics using this technique, and in some cases organisms could be identified to the species level, although this was only the case for organisms that were roughly 10 cm across or larger. Some confidently identified invertebrates include: Bat stars *(Patiria miniata),* giant sea star *(Pisaster giganteus),* and *Loxorhynchus* crabs. (Fig. 5)

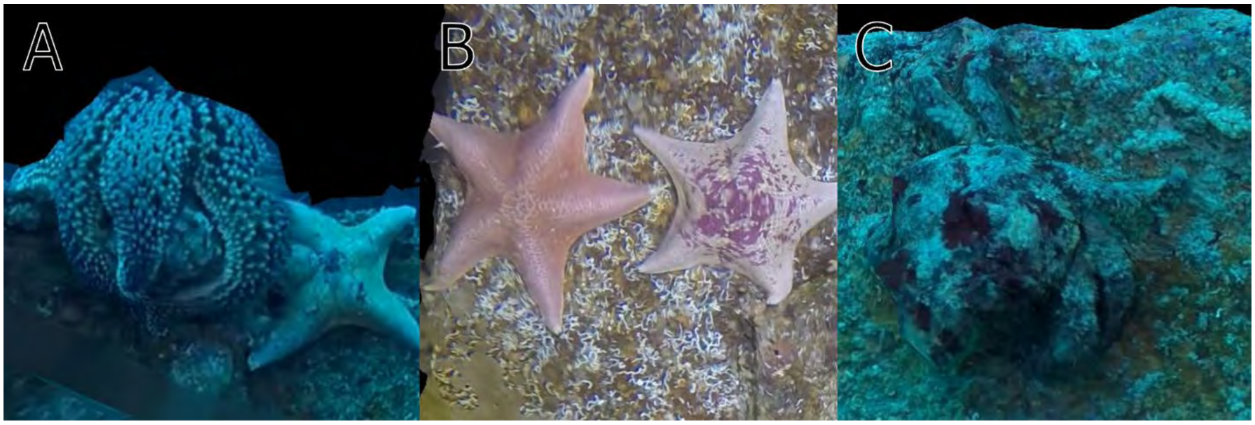

Figure 5. 3D Model screenshots of confidently identified invertebrates include: (A) *Pisaster giganteus*, (B) *Patiria miniata*, and (C) *Loxorhynchus* crabs.

Model assessment part 3: Virtual reality integration

Finally, I investigated future possibilities to include virtual reality integration. I believe this would be an informative and intuitive way for the public to engage with the undersea wonders of MBNMS. Fortunately, Sketchfab (an online 3D model viewing platform that is seamlessly integrated with Agisoft's Metashape) allows for viewing models in virtual reality. Early exploration of this functionality is promising but requires additional equipment, like a VR headset, to implement. In addition to offering VR integration, Sketchfab allows viewers to load and explore 3D models on their cell phones (external link). This allows us to bring our seafloor MHR models right into the pocket of the public!

Section 4: Recommendations

As with everything, building 3D models of MHRs from ROV collected videos comes with a set of trade-offs. If the intended use of the model is to identify all of the squishy worms living on a wreck or moving organism such as fish or kelp swaying in the swell, then the raw ROV video is likely a better choice than a 3D model. While it is certainly possible to generate a model with "video-like" resolution, you begin to run up against considerably longer processing times and much larger file sizes. If the intent is to allow anyone with an internet connection, and maybe not always the best speeds, to view the model from any computer (including their cell phone), then it seems the two best options are larger less detailed models and smaller more detailed models.

Larger, comparatively less detailed models (Fig. 6) are valuable for capturing the general structure, placement, and orientation of parts of a wreck. Additionally, video to generate models of this quality involves less ROV entanglement risk and is faster to collect, as it can be taken from a greater distance from the wreck. Being farther from the wreck allows the pilot to navigate the target more quickly without fear of entanglement.

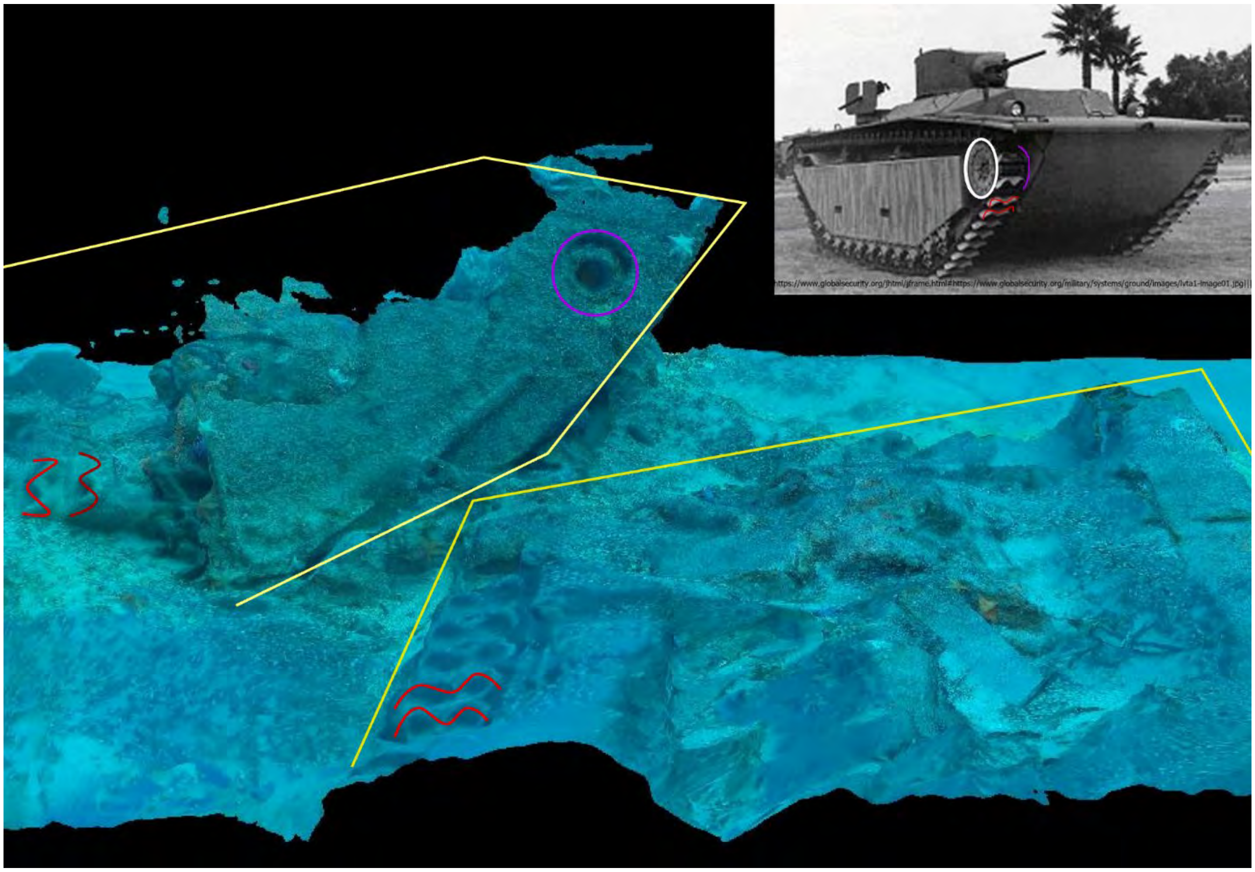

Figure 6. An "overview" of the entire Mating Amtracks wreck 3D model (external link). Notice two Amtracks (outlined in yellow), the "M-shaped" treads (red), and gear shaft port hole (purple).

Smaller, comparatively more detailed models (Fig. 7) require the pilot to maneuver around the target much more carefully. This becomes particularly concerning when additional lights need to be attached to the ROV to resolve color in deeper darker waters, as the closer you are to something, the more likely you are to collide with or become tangled in it. That said, these smaller more detailed models do a great job of accurately capturing color and small detail (like individual worm tubes).

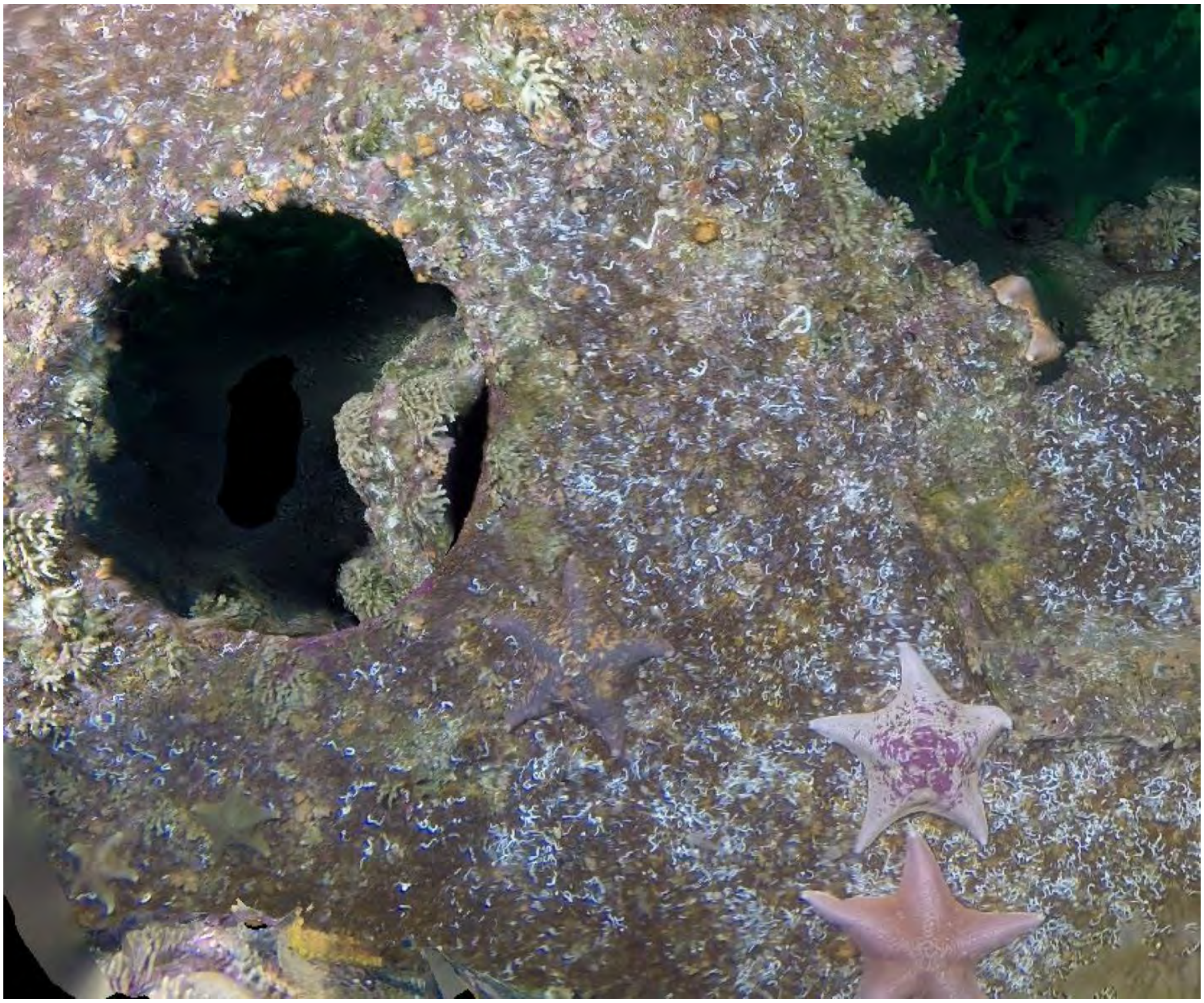

Figure 7. A snapshot of my 3D model of the Mating Amtracks (external link) showing the level of detail possible when attempting high resolution modeling

I think that a combination of these two approaches would make for the most informative option. A large model that captures the entirety of the target through clear "virtual water" will allow the end user to see an MHR in its entirety at one glance, which is only possible otherwise under the best of underwater conditions, if ever. Even at these lower resolutions, it's possible to recognize some of the larger, more distinctive organisms, such as kelp, sea stars, and large anemones growing on the structure. These less-detailed "overview" models can be augmented with "detail" inset models of smaller parts of the wreck that maybe have some interesting feature (or are safe and easily accessible for the ROV).

Section 5: Future Steps

My initial trial revealed that it is possible to generate 3D models of MHRs from video collected by small ROVs operated from small boats, but it also revealed some limitations with my initial approach and provides direction for improvement of the technique. I found that there are two areas in need of further development: 1) optimizing video collection techniques to improve model resolution and color, and 2) incorporating a more precise system for including calibrated length measurements, so that the models can be scaled to actual size.

Optimization of video collection techniques can be broken into three sub-categories: A) finding and maintaining an optimal distance between the camera and the subject, B) determining (and then practicing) how to pilot the ROV in terms of things like speed, steadiness, and viewing angles, so that the resulting video lends itself to efficient and effective conversion to a high-quality 3D SfM model, and C) optimizing the number, arrangement, and brightness of lights to achieve good color and spatial resolution in the model without seriously increasing the risk of entanglement, reducing ROV maneuverability, or seriously limiting ROV battery life (since small ROVs and their lights are often powered by rechargeable on-board batteries.)

Based on our trials, the optimal imagery collection distance seems to be between 0.5 m and 1.0 m. These numbers however are rough estimates based on the collected video. Ethan Switzer, another student working in Steve Moore's lab at CSUMB is currently (Fall 2020) developing a laser system to assist the ROV pilot in maintaining an optimal distance.

The optimal piloting pattern seems to be, "crab-walking" the ROV sideways at a slow enough speed for the camera to capture crisp imagery. This specific speed will depend on what camera is being used and requires some practice to fine tune. That said, for less experienced pilots, moving the ROV to allow for roughly 80% overlap between "parking" and filming also results in a good model (but requires additional steps to remove redundant images). Ultimately, these are simply suggestions and will be dependent on the skills of the pilot. Consequently, the most reliable way to ensure smooth, consistent, in-focus frames is to allow for plenty of piloting practice. I would also advise any would-be pilots to familiarize themselves with how Metashape aligns pictures to ensure they can capture imagery in an appropriate manner. I found Metashape is most effective when images have at least 60% overlap (although in underwater environments with less light closer to 80% is better) and are in focus and don't have any motion blur. This isn't always possible but should at least be considered when piloting.

I also found that mounting the GoPro below our on-board live feed camera and tilting it down at about 30° ensured that we captured our target. This configuration however introduces parallax as our video capturing camera isn't the same as the camera being used to pilot the ROV. Fortunately, the frame of view on our GoPro was sufficiently wide enough that with enough piloting practice parallax was not a major obstacle for us.

Our current ROV configuration only includes 2 dimmable 1,500 lumen "headlights" that shine roughly straight ahead. Large research ROVs like the *Doc Ricketts* are outfitted with up to six 17,700 lumen lights. In order to increase our lighting capabilities, Maggie Seida is developing a "bolt-on" lighting rig that will allow for customizable in-field adjustments of the lighting angles. This may prove valuable to capturing high fidelity close-up video while minimizing the risk of entanglements. Increasing the number and brightness of lights attached to our ROV would allow us to more effectively illuminate larger areas at a greater distance. More and brighter lights also come with disadvantages as additional lights increase battery draw. In the case of our BlueROV2, each light we include has a draw of up to roughly one amp, and our battery is rated for 18 amp hours. Additionally, depending on the angle of the lighting, and the present turbidity, there's the potential for significant backscatter. Backscatter can be minimized by placing our lights further apart, but this increases the risk of entanglement. These lighting issues and others will be further addressed as Maggie continues to develop her lighting rig.

In addition to optimizing imagery composition, it would be valuable to include some way to make accurate size measurements. A sense of scale is important as certain wrecks could be identified by their size and last known location and could be used to track changes over time. Additionally, an accurate sense of scale is required in order to create realistic fully explorable virtual reality exhibits of MHRs. A common method for doing this using ROVs is a parallel laser system, also in development by Ethan Switzer. Including a few clear frames with the projected parallel lasers in them in the model will allow the modeler to add measurement points to the model giving it scale in 3D space.

Section 6: References and Software

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Section 7: Additional Resources

A brief YouTube video introducing this project (https://youtu.be/VEUnCdHSmVo)

My 3D model of the "Mating Amtracks" (https://sketchfab.com/3d-models/mating-amtraks-e592c926dfdd4e68a6d4e402a00ef93d)

My 3D model of the level of detail possible with this technique (https://sketchfab.com/3d-models/mating-amtracks-detail-99e81fdbdd674bcdb1fadb3f13e80934)

The BAUE report prepared in 2012 (http://www.baue.org/projects/amtracks/#:~:text=The%20Mating%20Amtracks%20are%20located,and%20is%20surrounded%20by%20sand.)

Section 8: Map data sources

MBNMS boundary layer (https://sanctuaries.noaa.gov/library/imast_gis.html)

ESRI. "Imagery" [base map]. Scale not given. (Figures 1 and 2)

US state boundaries (https://hub.arcgis.com/datasets/TrainingServices::us-state-boundaries/data)