U.S. DEPARTMENT OF ENERGY

Advanced Laboratory and Field Arrays

Task 2: Technical Report for Autonomous Monitoring & Intervention

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TASK 2: AUTONOMOUS MONITORING & INTERVENTION

INTRODUCTION

The goal for this task was to develop software for an autonomous underwater vehicle (AUV) capable of performing inspection, monitoring, and intervention operations in marine renewable energy arrays, employing motion planning and probabilistic navigation methods. Inspection and manipulation tasks were chosen to be applicable to multiple device types without requiring expensive components. Minimal human intervention reduces costs and also improves efficiency. Using AUVs for inspection and monitoring with limited human intervention and low-cost infrastructure is viewed as critical to the strategy for bringing down O&M costs. The final deliverable for this task was to enable a decrease in the time for maintenance and intervention in marine renewable energy arrays by up to 30% versus using tele-operated ROVs.

BACKGROUND

This report outlines marine field demonstrations for manipulation tasks with a semi-Autonomous Underwater Vehicle (sAUV). The vehicle is built off a Seabotix vLBV300 platform with custom software interfacing it with the Robot Operating System (ROS) [Lawrance et al., 2016]. The vehicle utilizes an inertial navigation system available from Greensea Systems, Inc. based on a Gladiator Landmark 40 IMU coupled with a Teledyne Explorer Doppler Velocity Log to perform station keeping at a desired location and orientation. We performed two marine trials with the vehicle: a near-shore shared autonomy manipulation trial and an offshore attempted intervention trial. These demonstrations were designed to show the capabilities of our sAUV system for inspection and basic manipulation tasks in real marine environments.

SUBTASK 2.1: EVALUATING AUV SYSTEMS FOR INSPECTION, MONITORING, & INTERVENTION

RESULTS AND DISCUSSION

This section briefly summarizes the industry review and identifies some of the more promising research applications as well as provides information from four companies working in the area of marine renewable energy. This industry review demonstrates the potential benefit of autonomy in the marine renewable energy industry.

Industry Response

We contacted representatives at the following marine energy companies asking for feedback regarding the following items:

1. A short list of ROV-executed and diver-executed tasks, with estimated execution times per device, you foresee for array-scale installation, operation, and maintenance.
2. An estimate of how much time you believe could be saved by adding autonomy to these tasks.
3. The challenges you see in integrating autonomy into these tasks.

Companies contacted who design Wave Energy Converters (WECs) and Current Energy Converters (CECs):

1. M3 Wave LLC - (WEC designers)
2. Columbia Power - (WEC designers)
3. Ocean Renewable Power Company (ORPC) - (CEC designers)
4. Verdant Power - (CEC designers)

All four companies expressed interest in the use of autonomous vehicles for monitoring and intervention operations and responded with detailed e-mails. We have compiled and summarized the responses below. **Overall, we have identified multiple tasks where companies believe that a decrease in deployment time of 30% or more is possible with AUV operations (see detailed notes below). In cases where the ROV would not decrease the completion time, companies have stated that the elimination or reduction of divers would results in substantial cost savings.**

Deployed system examples:

- **M3 Wave's APEX:** sits stationary on the ocean floor and converts the pressure wave under ocean waves into electricity. M3 Wave LLC performed an open water deployment in Sept, 2014. They performed ROV imaging testing and sample collection in the months leading up to the project but shifted to divers during the actual deployment and operation for several reasons.
- **ORPC's tidal turbine system in Cobscook Bay, Maine**: Many of the activities ORPC performs subsea require a degree of flexibility to deal with unintended issues problems as they arise. They therefore depend on divers for subsea procedures right now. As they develop their technology and start to perform repeated operations they will be looking to remove the diver element from this work. Also, as they move to deeper water and more extreme environments, they believe that divers will be infeasible. Water conditions are 100 feet at MLLW, cold water, visibility of up to 10 feet at depth, slack water events from 20 to 40 minutes long. Given the depth, they are on the margins of requiring a decompression chamber, especially at high tide. They use hardhat divers for heavy construction work, and scuba divers for inspection and light construction activities. Insurance for these divers has been problematic.

ROV use cases identified:

- **Monitoring of sediment (M3 Wave):** Company's initial goal was to use the ROV for monitoring of sediment on and around the device during the multi-week test and take sediment samples. They chose a Deep Trekker 2 due to its small size and on-board lithium-ion battery, which made topside support equipment minimal. Their intent was to gain enough operational confidence to mount the ROV to PWCs that they were using for sonar mapping of the area. This would have allowed them to launch from shore and be on station in 6 minutes versus the 3-4 hours needed for a vessel to transit the Columbia Bar and motor to the site. Ultimately, the data quality and operational confidence was not adequate, and they added dive days to conduct the monitoring operations. By way of comparison, the ROV cost the same as ~2 dive days.
- **Wet connect and turning valves (M3 Wave):** Company identified these activities as irregular or infrequent deployment and O&M activities. In most of the cases of initial deployment as well as unplanned maintenance, they would consider divers initially. In those cases, uptime needs and

flexibility requirements would offset any savings that might be gained from a complex AUV conducting a complex operation. Companies would pay to have divers standing by or even in the water anyway, monitoring the AUV in case of malfunction.

- **Biological and benthic monitoring (M3 Wave):** Company identified these activities as having a large potential benefit of AUV operation. This might include video, sediment sampling, 3D sonar imaging of sediment transport, EMF monitoring, acoustic monitoring, etc. The repeated, monotonous, lengthy aspects of this process make it expensive to do with divers long term. This task was identified as one that might have a substantial benefit from ROV operations.
- **Preventative maintenance (M3 Wave):** This might include scraping or removal of bio-fouling, monitoring of mechanical and eletro-chemical wear indicators, system re-charge, video logging, etc.
- **Video inspection of installed power and data cables (ORPC):** Cables require regular video inspections from shore to the subsea central connection unit, approximately 3000 feet of length, with the cables alternatively buried and exposed. Finding the cables visually can be problematic. Navigating a GPS defined route would be more efficient. Time estimate 1 hour of inspection time. *Possible to reduce subsea time by ½ if they do not need to search for the cable.* This inspection is performed yearly, with an emphasis on benthic impacts.
- **Connecting TidGen Unit (ORPC):** Company has a subsea central connection unit into which cables from each TidGen would be fed, connected, and then transmitted on one cable to shore. To connect a TidGen unit requires (1) lifting a cover, (2) locating the connector box, (3) removing three wet mate dummy plugs (2 power, 1 data), (4) connecting the TidGen unit, (5) retrieving the dummy plugs, (6) replacing the lid. Time estimate for this is 40 minutes. Most of the diver time is spent in locating the proper elements and removing the dummy plugs, which can be difficult to remove. Creating a stab plate connector would reduce time and possibility of error. *The AUV approach would reduce time for this operation by approximately ½.*
- **Electrical connection of TidGen TGU to the array cable (ORPC):** They disconnect the power and data cables at the TidGen in order to retrieve the unit cleanly. These are wet mate connectors (again 2 power and 1 data). A full dive is required (40 minutes). *A stab plate arrangement will be required and again I would estimate a reduction in time by ½.*
- **Mechanical connections of TidGen to foundation (ORPC):** This consists of a series of 10 mechanical connections spread along the length of the turbine support frame. They have a cross-flow turbine, which is approximately 100 feet long. This work is performed by a team of 4 scuba divers, and each diver can work on 2 to 3 different connections in the course of a dive. This actually takes about 10 to 15 minutes and is quite efficient. This can be automated, but ORPC is not sure it can be made faster. The obvious way to reduce time is to reduce the number of connections. The unit is then connected to a rigging system from a surface crane and hoisted to the surface. Rigging time is approximately 15 to 20 minutes, and depends on how well the surface vessel can maintain station over the unit.
- **Inspection (turbine and ancillary equipment) and deployment, maintenance, retrieval (ancillary equipment) (Verdant Power):** Company states they would be interested in ROV/AUV operation if the cost and performance were competitive with their current alternatives. They believe there are certain operations where this may be true. However, they currently do not have enough information about the operational capabilities of these vehicles and how those capabilities impact cost, deployment, etc. Verdant Power sees value in the use of ROVs, and potentially autonomous

ROVs, specifically in the following areas: inspection (turbine and ancillary equipment) and deployment, maintenance, retrieval (ancillary equipment).

- **Periodic inspection of WEC hull and mooring with SCUBA diver(s) (Columbia Power)**
    - Estimated time: 2 divers 45 minutes each, 2 person support crew topside (deckhand and captain)
    - Frequency: once per quarter
    - Estimated time savings from autonomy: Inspection time assumed the same, but no divers and same support crew.
    - Total savings: 90 minutes per WEC per quarter
    - Challenges: Camera vision inspection with an AUV might have limitations as compared to a diver doing a hands on check.
- **Inspection and attachments during WEC ballast evolutions (Columbia Power)**
    - Estimated time: 2 divers 30 minutes each, 2 person support crew topside (deckhand and captain)
    - Frequency: once per 10 years
    - Estimated time savings from autonomy: Time assumed the same, but no divers and same support crew.
    - Total savings: 60 minutes per WEC per ten years
    - Challenges: Camera vision AUV inspection has limitations as compared to a diver doing a hands on inspections and attachments.
- **Inspection and attachments during WEC mooring installation (Columbia Power)**
    - Estimated time: 2 divers 30 minutes each, 2 person support crew topside (deckhand and captain)
    - Frequency: once per 10 years
    - Estimated time savings from autonomy: Inspection time assumed the same, but no divers and same support crew.
    - Total savings: 60 minutes per WEC per ten years
    - Challenges: Camera vision AUV inspection has limitations as compared to a diver doing a hands on inspections and attachments.
- **Unplanned intervention and inspection (Columbia Power)**
    - Estimated time: 2 divers 120 minutes each to address an unexpected failure identified during inspection, 2 person support crew topside (deckhand and captain)
    - Frequency: once per 5 years
    - Estimated time savings from autonomy: Inspection time assumed the same, but no divers and same support crew.
    - Total savings: 240 minutes per WEC per five years
    - Challenges: Repair event may not be addressable with AUV
- **Hull cleaning (Columbia Power)**
    - Estimated time: 4 divers 120 minutes each to clean critical surfaces
    - Frequency: 1 year
    - Estimated time savings from autonomy: Cleaning time by AUV may take longer and would require item 1 above to be implemented. Savings would be that a robot is doing perpetual cleaning on the array rather than divers and a support crew.

- **Hull cleaning - continued**
    - Total savings: 8 hours per WEC per year
    - Challenges: implementing 1 above.

Main issues with ROV Ops:

- **Poor visibility:** This was in part due lighting and camera suitability (or lack thereof). Multiple companies are working on improvements to cameras and lighting.
- **Tether management:** Companies were attempting to operate in the near-shore area where station keeping of the launch vessel was critical, yet they could not use bow thrusters for lateral control due to risk of umbilical ingestion.
- **Navigation/situational awareness:** Companies had challenges finding/returning to the same spot for monitoring purposes since they lacked on-board compensated GPS or hi-res inertial nav.
- **Servicing requirements:** Close proximity from array to dock could allow AUV transit to the array without vessel support. A charging station and AUV accessible/exchangeable tool crib located within the array would allow for mission flexibility without bringing AUV back to dock.
- **Umbilical:** Umbilical entanglement is one of the biggest operational limiters. It even affects how and where they put marker buoys, since two cables within 100m of each other will often wrap around each other and intertwine. Also providing a benefit would be a "wireless" ROV even if it was not autonomous.

Companies see a substantial benefit to going autonomous for the following tasks:

- **Persistence/low cost mob/demob:** With an autonomous system, if it can recharge off an underwater junction box, would allow 24x7 monitoring**.** By avoiding the need to mobilize and demobilize deployment and recovery assets for every ROV/AUV mission, one can save significant amounts of O&M capital. One thing to keep in mind, the cost of an ROV deployment rig may not be much less than a diver platform when operations are in water shallow enough to facilitate conventional non-hardhat diving. A small boat, all day charter is required either way. But, if one could leave the robotic asset on the bottom for an extended period, it would save significantly in deployment vessel cost for long term operational monitoring of an array.
- **Surf entry:** As long as you have the power and the navigation capability, launching an ROV like you'd launch a PWC or Dory would potentially be feasible. For M3 Wave, shore launch puts them within 1 mile of the target site versus taking a vessel out of Astoria or Tongue Point, which is many miles.
- **Reducing risk to divers:** Divers are also error prone and their work is not easily inspected by QA/QC. Navigation and orientation for divers is difficult underwater as they are typically relying on site and can get easily disoriented. Down lines are often required for the divers and this leads to excessive lines in the water which could foul the unit.

Challenges identified for autonomous operation:

- **Station keeping:** In nearshore, relatively shallow environment (7-10 fathoms) surge is a factor. Companies have considered adding navigation aids to WECs with ROVs in mind - either "garages" for safe parking, optical indicators for navigation, metallic segments for magnetic adhesion and stabilization, etc. Companies think very soon you'll see more and more WEC designs evolve with DFRM (Design For Robotic Maintenance) in mind.

- **Situational awareness:** It's not enough to navigate to within view of an optical target. If the ROV is performing tasks like sediment sampling, the operator will need to specify where to take samples from (to within 1m or less resolution). That is a nontrivial sensor fusion activity. Some sample sites are away from the device(s), and putting extra sample site targets is not ideal due to permitting and reliability issues with anything left on the floor. Even small ROV's have a special sensor riser to get the compass sensor away from the ROV housing. Companies have trialed some small ROVs for inspection and found that the tether is the real drag on the system and makes the system uncontrollable.
- **Robustness.** Companies have seen some of the ROV/AUVs under development at universities and believe some are going to have a challenge in the real ocean environment. Imagine an AUV conducting a video transect down the length of the WEC, recording video of biofouling. Even the best navigation and station keeping thrusters in the world cannot predict when a big surge will come through and bang the robot against the steel side of the WEC. Need to be able to shake it off and keep motoring.
- **Fault recovery:** What happens when a failure happens? How does the 'bot know there's been a failure? Is the default mode "return to surface" where there is increased likelihood of the AUV becoming beached? Or do you drop anchor, pop a marker and phone home? When many ROVs have an issue, they are hauled back up using the umbilical (which is conveniently designed to be robust enough for that purpose). If a piece of algae wraps around a prop, you'll want to be able to identify and compensate to enable completion of the mission and/or safe abort. In many cases, companies have pulled up ROVs after an open water operation with some minor prop fouling that was enough to cause noticeable thrust yaw.
- **Highly energetic tidal flows:** In some coastal waters, there are approximately 60 minutes with water speeds below 1 m/s at each slack tide. AUV would need to perform in these types of environments. This brings into question the load capabilities of these AUVs (e.g., how much lift, torque, etc. can they generate and sustain).
- **Flexibility:** Divers are inherently more flexible in their work approach. Scuba divers are actually very efficient in transiting to the work site. They reach depth and are working within 5 minutes, and because they work in teams there are 2 pairs of hands at work in parallel. Hardhat divers are the least efficient for reasons that are worth examining: (1) These divers are encumbered by tethers, and the working window available is extremely limited by the drag on the tether and by the entanglement possibilities of the tether. (2) One diver in the water limits the amount of work that can be done. (3) One diver in the water, having to move over a given distance limits the amount of productive time, as hard hat divers move slowly (tether management). (4) All of the divers and the ROVS are limited in the amount of working time that they have due to flow speeds.

Subtask 2.2: AUV navigation within MEC arrays

The goal for this subtask was to develop a navigation system for the AUV using probabilistic localization techniques by integrating sensor data from the inertial sensors, the Doppler velocity log, and the acoustic positioning system to minimize risk of operating AUV within MEC arrays. Developing navigation software that integrated various sensors modified the AUV. Station keeping ability to maintain altitude and position and to follow waypoints were achieved in pool tests and finally in a field deployment in the ocean.

Introduction and Background

This section presents results testing the station keeping abilities of a tethered Seabotix vLBV300 underwater vehicle equipped with an inertial navigation system. These results are from an offshore deployment on April 20, 2016 off the coast of Newport, OR (44.678 degrees N, 124.109 degrees W). During the mission period, the sea state varied between 3 and 4, with an average significant wave height of 1.6 m. The vehicle utilizes an inertial navigation system based on a Gladiator Landmark 40 IMU coupled with a Teledyne Explorer Doppler Velocity Log to perform station keeping at a desired location and orientation. The data from the sensors are fused using an Extended Kalman Filter, and a feedback control system is used to maintain desired position and orientation. Streaming data is available to the operator in real time, and changes to the vehicle's desired position and orientation can be made on the fly. Additional details on the system can be found in the workshop publication [1].

During the deployment, station keeping was performed at two different times, denoted P2 and P3. At time P2, station keeping was performed at a depth of 10 meters where initially the vehi-cle was allowed to drift unpowered, and then station keeping was turned on to compare the two different responses. At time P3, station keeping was performed at the maximum depth for the de-ployment, defined to be approximately 5 meters of altitude from the seafloor, which corresponded to a depth of approximately 35 meters. Dive time was approximately 80 minutes total for the vehicle.

Section 2 talks briefly about the data set and associated MATLAB code that will allow the user to investigate the data on their own. Section 3 reports the results for each of the station keeping tests.

2 Data Set

The data set was obtained by parsing the command messages from the Greensea Integrated Navigational System which provided relative position and heading information. Each of the data files is a *.mat file which contains the following:

- x: the estimated relative x position measured from the desired position in meters
- y: the estimated relative y position measured from the desired position in meters
- z: the estimated relative z position measured from the desired position in meters
- heading: heading of the vehicle in degrees
- t stamp: time at which the data is received in UNIX time

Provided with the data set is a MATLAB script to load the data and produce the graphs provided in this report. Additional detail is available in the provided README file. The MATLAB code and data set have been submitted for inclusion in the Department of Energy data repository.

3 Results

The results presented here report both the root mean squared error (RMSE) and the mean position error (ME) for station keeping at a location. Additionally, the RMSE and ME heading control for the vehicle is reported. Both P2 (10 m) and P3 (35 m) consisted of two different attempts at station keeping. For all positional graphs the green x shows the beginning, and the red circle shows the end of the data collection.

3.1 Summary of Results

The results demonstrate that the station keeping system produced mean position errors below 0.45 m and 2.5 m in the two 10 m depth trials, and mean errors below 0.6 m and 1.8 m in the two 35 m depth trials. The mean heading error was below 1.4 degrees and 15 degrees in each of the 10 m trials and below 2.3 degrees and below 5 degrees in each of the 35m trials.

The target values for this deliverable were less than 5 m error in position and less than 45 degree error in orientation in sea state 3 or above. These target values were met for both the 10 m and 35 m depth in sea states ranging from 3 to 4. The shallower depth showed somewhat higher errors, likely due to increased disturbances from ocean waves. Overall, these error values are sufficiently low for the intended goal of inspection and monitoring in wave energy arrays. Graphs showing the detailed results are presented below.

3.2 10 meter Depth

Figure 1 compares station keeping at 10 meter depth to approximately 200 seconds of drifting at the same depth.

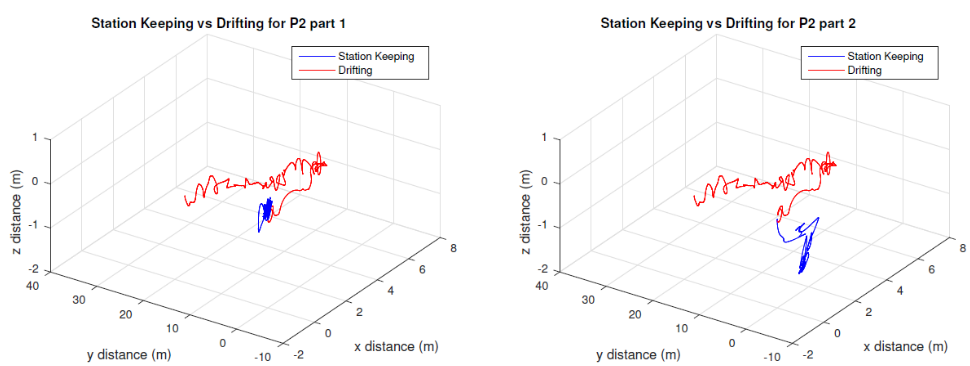


Figure 1. Comparison of station keeping versus drifting at 10 m depth (Left Trial 1: 200 seconds drifting and 151 seconds station keeping, Right Trial 2: 200 seconds drifting and 86 seconds station keeping)

Figure 2 shows the position of the vehicle as it attempted to station keep at 10 meter depth in two trials for 151 and 86 seconds respectively. Figure 3 shows both the RMSE and ME error for all three directions as well as the overall error.

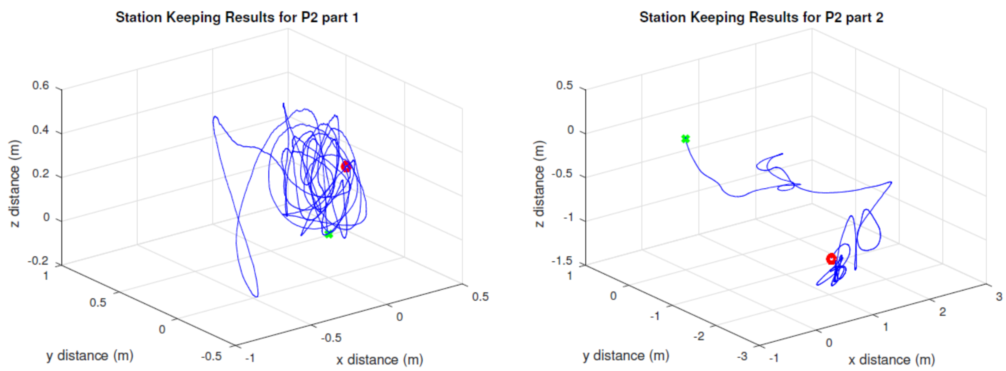


Figure 2. AUV Position Track for 10 m depth station keeping (Left Trial 1: 151 seconds, Right Trial 2: 86 seconds)

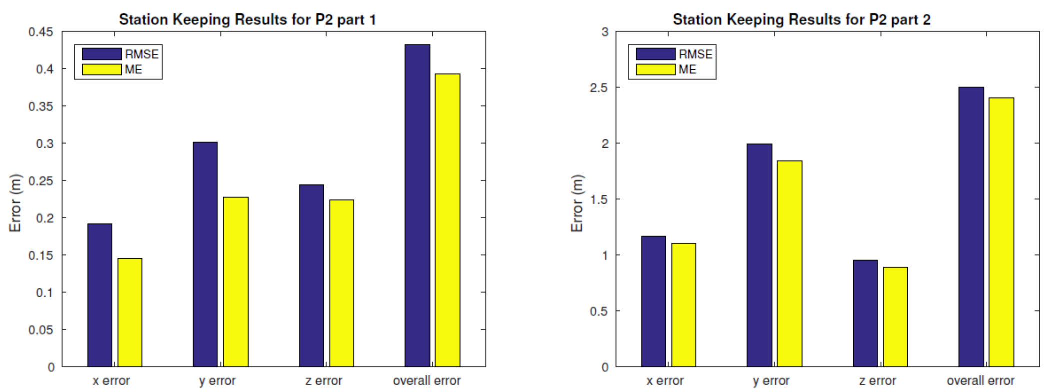


Figure 3. Root Mean Squared Error (RMSE) and Mean Error (ME) error for station keeping at 10 m depth (Left Trial 1: 151 seconds, Right Trial 2: 86 seconds)

3.3 35 meter Depth

Two different station keeping results are presented here for the 35 meter depth. **Figure 4** shows the positional track of the vehicle as it performed station keeping for 72 and 186 seconds respec-tively. **Figure 5** shows the RMSE and ME.

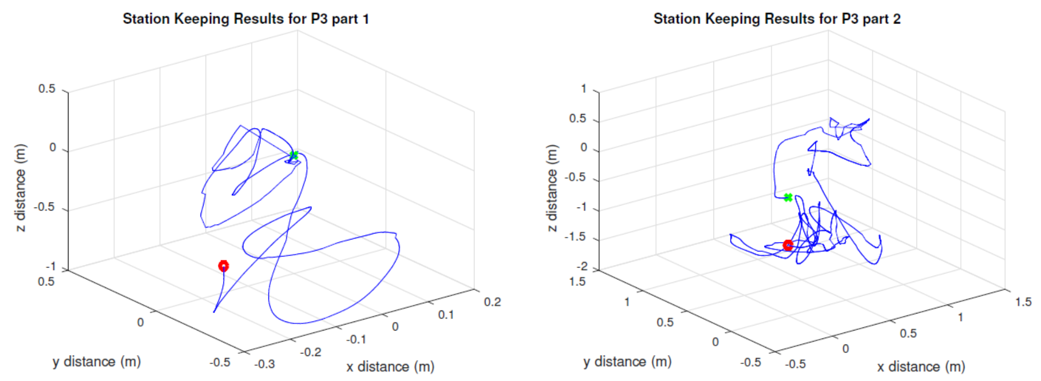


Figure 4. AUV Position Track for 35 m depth station keeping (Left Trial 1: 72 seconds, Right Trial 2: 186 seconds)

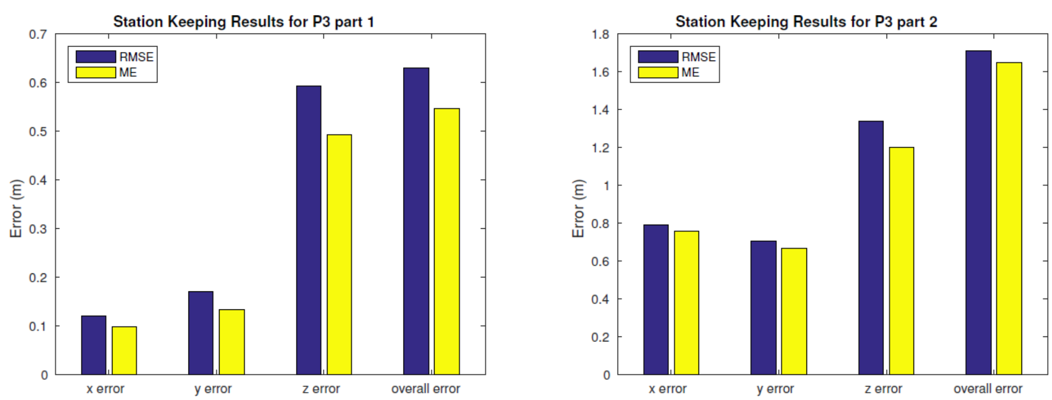


Figure 5. Root Mean Squared Error (RMSE) and Mean Error (ME) error for station keeping at 35 m depth (Left Trial 1: 72 seconds, Right Trial 2: 186 seconds)

3.4 Heading

Figures 6 and 7 show the RMSE and ME for the heading during station keeping. Each depth has one run where the error is very low and one run where the error is higher. This is due to an initial oscillatory behavior seen where if the vehicle was far from the desired heading the vehicle would overshoot when trying to correct and oscillate around the desired position. While this behavior would quickly disappear, this large initial error had an effect on the RMSE. In contract, the ME shows that this initial error was an outlier and the vehicle settled down to a controlled state quickly.

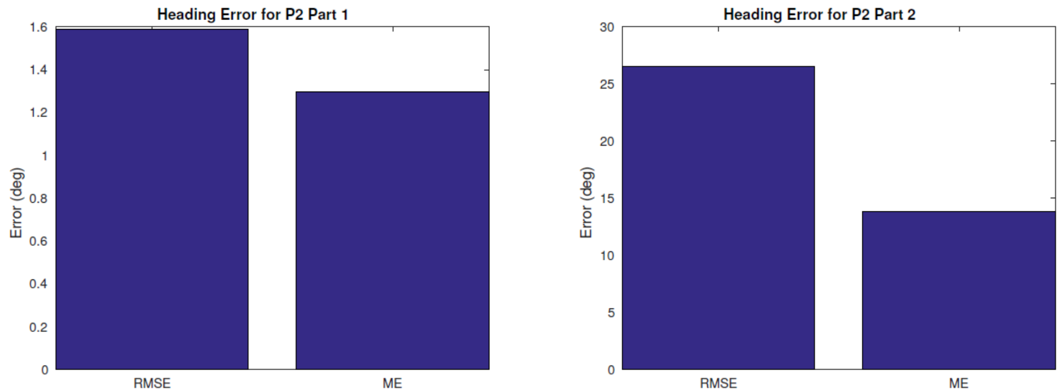


Figure 6. Heading error for P2 part 1 at 10 m depth (Left Trial 1: 151 seconds, Right Trial 2: 86 seconds)

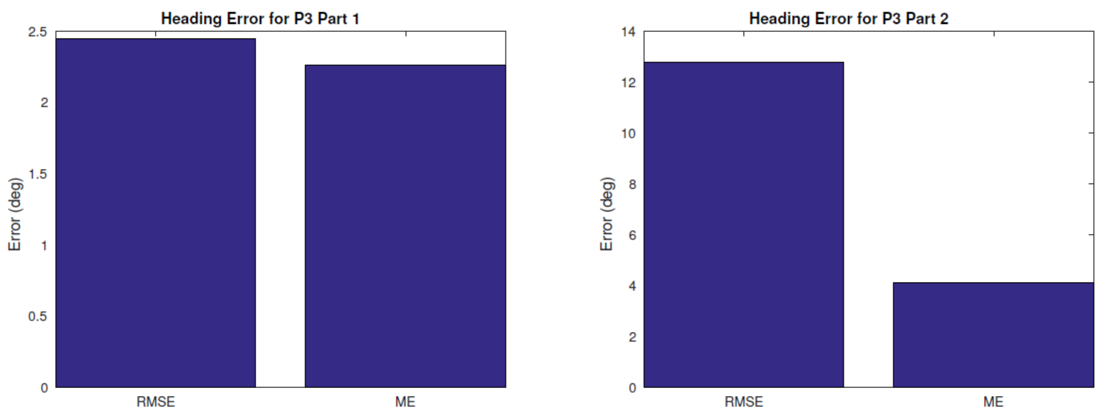


Figure 7. Heading error for P3 part 1 at 35 m depth (Left Trial 1: 72 seconds, Right Trial 2: 186 seconds)

REFERENCES

N. Lawrance, T. Somers, D. Jones, S. McCammon, and G. Hollinger. Ocean deployment and testing of a semi-autonomous underwater vehicle. In Proc. IEEE Int. Conf. on Robotics and Automation Workshop on Marine Robot Localization and Navigation, Stockholm, Sweden, May 2016.

Subtask 2.3: Autonomous manipulation and monitoring of marine renewable energy arrays using AUVs

This subtask developed monitoring and manipulation capabilities using motion planning techniques for deployment in energetic MHK environments, including the development of mapping capabilities in software on the AUV. Software was demonstrated in pool tests and in a field deployment in the ocean. Software enables the AUV to manipulate the environment, demonstrated in pool tests and in a field deployment in the ocean. The functional requirement to achieve the target 30% reduction in mission time when compared to mapping and manipulation performed by a human operator relative to the baseline established in Subtask 2.1 is discussed in the following section.

1 Introduction (M2.3.1)

This section presents results from tests to demonstrate underwater mapping capabilities of an underwater vehicle in conditions typically found in marine renewable energy arrays. These tests were performed with a tethered Seabotix vLBV300 underwater vehicle. The vehicle is equipped with an inertial navigation system (INS) based on a Gladiator Landmark 40 IMU and Teledyne Explorer Doppler Velocity Log, as well as a Gemini 720i scanning sonar acquired from Tritech. The results presented include both indoor pool and offshore deployments. The indoor pool deployments were performed on October 7, 2016 and February 3, 2017 in Corvallis, OR. The offshore deployment was performed on April 20, 2016 off the coast of Newport, OR (44.678 degrees N, 124.109 degrees W). During the mission period, the sea state varied between 3 and 4, with an average significant wave height of 1.6 m. Data was recorded from both the INS and the sonar.

During the deployments, the vehicle captured images of objects from multiple view points. In doing so, the vehicle experienced a wide range of motion (e.g. translational, rotational, and translational/rotational combinations). During the pool deployments, the vehicle primarily observed an “X” shaped object. Square, “T”, and triangle shaped objects were also observed. During the offshore deployment, the vehicle observed an underwater sinker block. The data recorded from these deployments was used to reconstruct the objects in 3D for the purpose of mapping.

The rest of this report is organized as follows: Section 2 briefly describes the parameters of the data set and the associated code files that allow the user to interact with the data. Section 3 reports the results of the reconstruction experiments.

2 Data Set

The data sets used in the reconstruction experiments is comprised of two main parts: navigation data and sonar imaging data. The vehicle navigation data is presented in the vehicle’s local coordinate system. Each of the data points contains the vehicle’s pose and a time stamp. The vehicle’s pose is represented as a position (x, y, z) in meters and an orientation (roll, pitch, yaw) in radians. The time stamp represents the vehicle’s local time at which the data point was generated. The sonar imaging data is represented as 2D grayscale images. In these images, 255 (white) represents a strong acoustic return while 0 (black) represents no acoustic return.

We provide two data sets from our experiments. The first is from the offshore de-ployment that images a mooring sinker block ('sinker block data.mat'), and the second is from the indoor pool test ('pool data.mat'). Additionally, we provide our data processing files. These files consist of MATLAB scripts to view, annotate, and project feature points into the sonar images. A C++ template file is provided to aid the user in reconstructing 3D data points from their own annotated data. Additional details can be found in the README file. If the user further wishes to work with their own recorded data, we direct them to our ECD to CSV processing code, available at: https://github.com/osurdml/GeminiECD_Decoder.

3 Results

3.1 Summary of Results

In section 3.2, the results show that using acoustic structure from motion (ASFM) algorithms allows for objects to be reconstructed in 3D using object feature points identified in sonar images. Section 3.3 illustrates that while a large percentage of sonar images can be of low quality (and lead to poor 3D reconstructions), it is possible to automatically distinguish between low and high quality images by characterizing them in terms of their 2D Discrete Cosine Transform (DCT) coefficients. In only using the predicted high quality images, precise 3D reconstructions can be maintained.

The goal for this milestone was to achieve mapping reconstruction errors less than 50 cm. An "X" target object with known dimensions of 0.35 x 0.35 x 0.44 meters (length, width, height) was reconstructed in a swimming pool, and a sinker block measuring 1 x 1 x 1 meters was reconstructed from an offshore deployment in sea states 3–4. The 3D reconstruction estimated the length and width of the "X" target object at 0.43 x 0.43 m (height was not estimated due to viewing the object from above) and the length and width sinker block as 0.9 x 1.1 m. These errors of approximately 0.1 m meet the requirements of the milestone.

3.2 3D Reconstruction

Figure 8 shows the output of the 3D reconstruction for the "X" object from one section of recorded data from a pool deployment. For this reconstruction, the "X" feature points in the sonar images are first reconstructed into 3D space. Next, using the known object proportions, a dense 3D point cloud is created. The ground truth size of the "X" object is 0.35 x 0.35 x 0.44 meters (length, width, height). Note that for this reconstruction, one edge of the "X" is not present. This is due to the fact that in this section of the recorded data, that edge is not visible in the sonar images (it is hidden in the sonar's acoustic shadow). The 3D reconstruction estimated the length and width of the "X" target object as 0.43 x 0.43 m compared to the ground truth of 0.35 x 0.35 m.

Figure 9 illustrates that even in the challenging case of the offshore deployment, a reasonable reconstruction of the sinker block's feature points is still able to be obtained. The length and width of the sinker block was estimated as 0.9 x 1.1 m (ground truth of 1 x 1 m), giving approximately a 10% error.

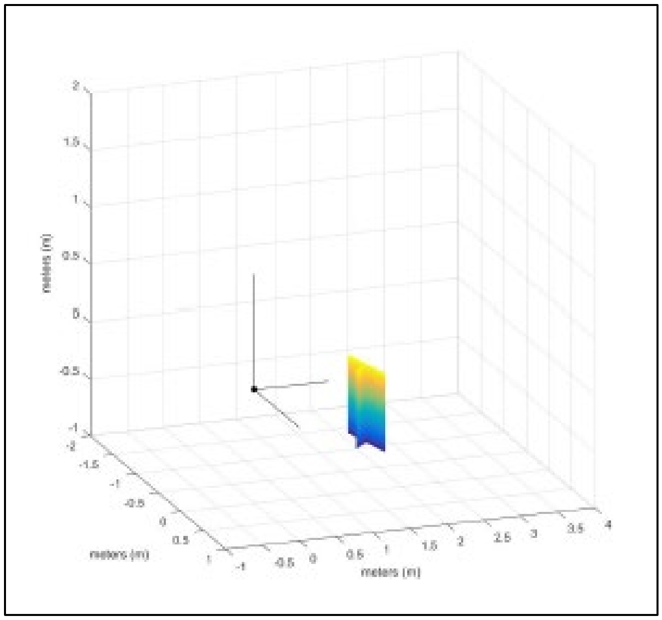


Figure 8. 3D point cloud reconstruction of a known object (3D "X") during a pool deployment. Feature points are first identified in 2D sonar images by an expert user before being reconstructed using recorded navigation data. The denser 3D point cloud shown is then generated from known object proportions.

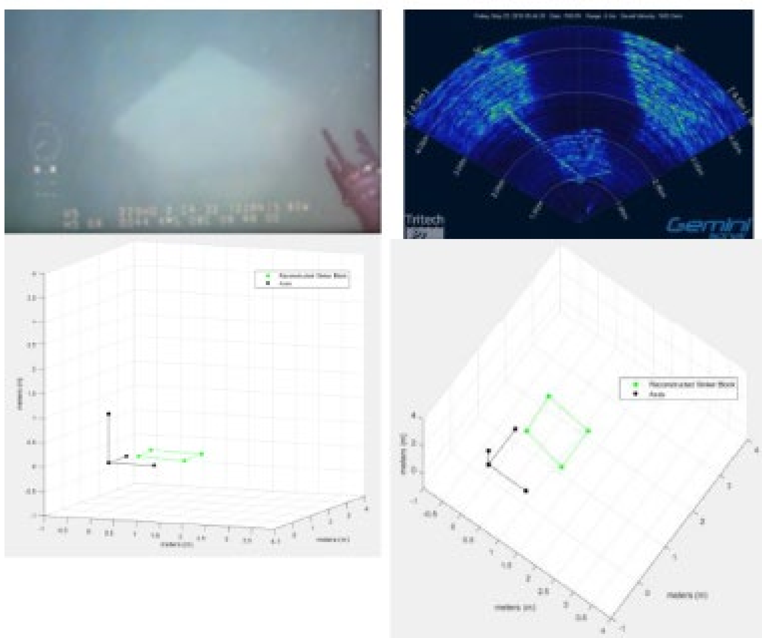


Figure 9. Top: Camera and sonar views of a mooring sinker block from the April 20, 2016 offshore deployment. Bottom: Two views (left) and (right) of a 3D point cloud reconstruction of a mooring sinker block. Feature points are first identified in 2D sonar images by an expert user before being reconstructed directly from the sonar images (no navigation data was needed).

3.3 Sonar Image Quality Analysis

When low quality sonar images are used to identify object feature points, inaccurate and variable labels occur. Using inaccurate feature point labels in the 3D reconstruction process results in arbitrarily poor reconstruction errors. In the experiments performed, this error was observed to be on the order of 100% - 400% of the reconstructed object's size.

Figure 8 shows that across several pool tests, it can be seen that the majority (more than 75%) of sonar images captured can be considered low quality. Figure 4 shows an example of both low and high quality sonar images and their corresponding DCTs. By utilizing only the sonar images identified as high quality, we are able to achieve the reported reconstruction errors of approximately 10%-20%.

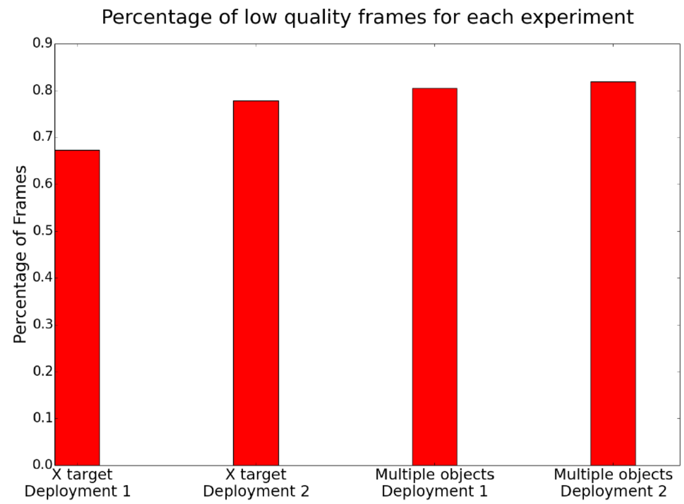


Figure 10. The percentage of frames that an expert user is unable to confidently hand label across multiple pool deployments. The first two data sets contain only an"X" shaped object, while the final two data sets contain the "X" shaped object among others (square, "T", and triangle shaped objects). On average, greater than 75% of the captured sonar images are not suitable for labelling.

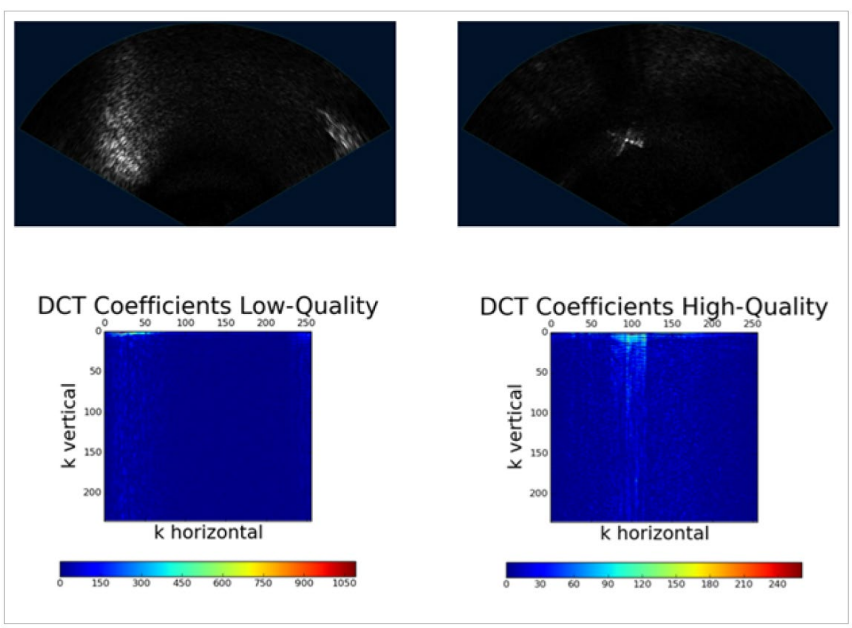


Figure 11. Low quality (left) and high quality (right) sonar images of the "X" object and their DCT coefficients. Coefficients closer to the bottom right corner indicate higher frequency information present in the image.

1 Introduction (M2.3.2)

This section outlines marine field demonstrations for manipulation tasks with a semi-Autonomous Underwater Vehicle (sAUV). The vehicle is built off a Seabotix vLBV300 platform with custom sotware interfacing it with the Robot Operating System (ROS) [Lawrance et al., 2016]. The vehicle utilizes an inertial navigation system available from Greensea Systems, Inc. based on a Gladiator Landmark 40 IMU coupled with a Teledyne Explorer Doppler Velocity Log to perform station keeping at a desired location and orientation. We performed two marine trials with the vehicle: a near-shore shared autonomy manipulation trial and an offshore attempted intervention trial. These demonstrations were designed to show the capabilities of our sAUV system for inspection and basic manipulation tasks in real marine environments.

2 Intervention Trial

2.1 Overview

The first trial combined autonomous navigation with handover to a human operator for manipulation of a fixed target in poor-visibility conditions. Our goal was to demonstrate that autonomous modes such as station-keeping and waypoint-following can be used to assist a human operator in navigating in a globally-fixed frame, while leveraging the human operator for the challenging maneuvers required for manipulation using only the visual camera. The trial was performed in Yaquina Bay on June 19, 2017. At the time of the trial (nearing mid-tide) the surface current was approximately 0.5 m/s. The water had limited visibility of around 1.5 m.

We constructed a basic manipulation target (**Figure 8**) where the goal was to grasp an 8 cm diameter steel U-bolt located approximately 1 m above the sea floor at a depth of approximately 5 m. The robot was (manually) driven to the target and attached by grasping the U-bolt with the sAUV gripper arm. Then, the robot was manually released, commanded to autonomously navigate to a waypoint 7 m south at a depth of 3 m and then return to the original target position and station-keep until the human operator took command. The human operator successfully re-grasped the target using only the visual camera. The entire process (from release to re-grasp) took approximately 100 s. For comparison, an operator familiar with the robot and task took approximately 50% more time to complete the task with a fully manual vehicle. Much of the time difference can be accounted for by the operator being required to constantly switch attention between data sources (navigation, sonar, camera) in order to maintain orientation and check whether target locations have been reached.

Figure 12. Photograph, onboard camera still image and ROS rviz visualization (clockwise from top left) of grasp target for shallow-water intervention trial (note that the time and date on the video overlay are incorrect, the trial was conducted on 19 June 2017).

The results in **Figure 9** represent the vehicle's own position estimate, and we do not have a true globally-referenced position of the vehicle. However, the grasp target was placed in the vehicle's frame of reference at the start of the trial to match its global position, and the target was weighted and did not move (in the global frame) during the trial. At the end of the trial the vehicle navigation frame had drifted approximately 0.7 m with respect to the true (globally stationary) position of the target. This was close enough that the human operator could see the target on the camera and manually complete the grasp.

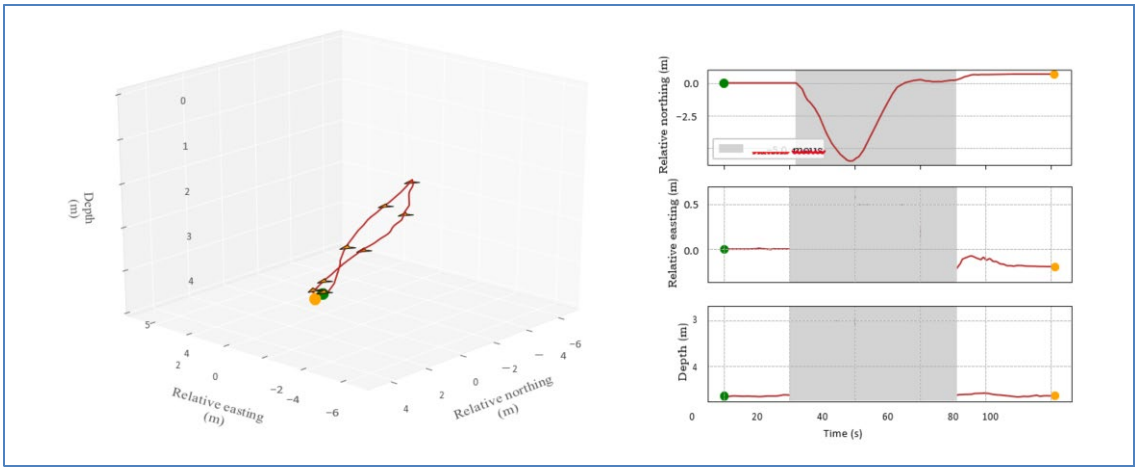
2.2 Data Description

Associated data from the intervention trials are provided with this report. The data is provided in the form of a plain text comma-separated values (csv) file consisting of records from the navigation estimate during the sequence of trials. There are two data files from the Yaquina bay intervention trial:

- **grasp trial1 p.csv** contains navigation solution estimates from the full set of attempted grasp and regrasp missions, and
- **grasp trial2 p.csv** contains a trimmed instance of a single successful grasp and regrasp trial (as shown in the results in **Figure 9**).

The data are saved in *.csv files with a header row describing the data contained in each column, and then subsequent rows of numerical data, where one row is all data recorded at a single time instance. Some of the more useful fields are:

- unix time sec time stamp in Unix time (s)



(a) 3D position track (b) Northing, easting and depth history

Figure 13. Navigation estimates during manipulation trial. Note that the vehicle had grasped the target at the start and end of the trajectory, so that the green (start) and yellow (end) positions of the trajectory should be approximately the same location in a fixed global frame. Heading arrows in 2a are shown in 5 s increments during autonomous motion. The grey region in 2b indicates the time during which the vehicle was under autonomous control.

- Relative position x the x position of the vehicle (m),
- Relative position y the ys position of the vehicle (m),
- Relative position z the z position of the vehicle (m), and
- Heading bearing of the vehicle relative to magnectic North (deg).

Provided with the data set is a Python script to load the data and produce the graphs provided in this report. Additional detail is available in the provided README file. The Python code and data set have been submitted for inclusion in the Department of Energy data repository.

3 AutoAMP platform deployment

For the second trial we assisted in deployment of the AutoAMP platform at a depth of 60 m and a location around 2 km offshore near Newport, OR (44◦ 33.0l N, 124◦ 13.75l W) on August 15, 2017. The primary goal for the AUV was to locate the platform and estimate the orientation after deployment to confirm that it had settled in a suitable position on the seafloor. A secondary goal was to perform a manipulation operation on the platform, namely grasp a U-bolt of similar dimensions as used in the previous trial. We successfully located the platform using sonar on the AUV and moved close enough to perform a visual inspection. We successfully surveyed the lander site and visually confirmed its position and orientation. Unfortunately, a malfunction of the Doppler velocity log navigation system resulted in poor navigation performance so we were unable to record navigation data or perform fully autonomous operations around the lander. We attempted manually grasping the lander but we did not want to risk damaging fragile equipment on the lander and due to currents and very limited operational time at the lander site we did not successfully complete a grasp. Images from on-board cameras can be seen in **Figure 10.**

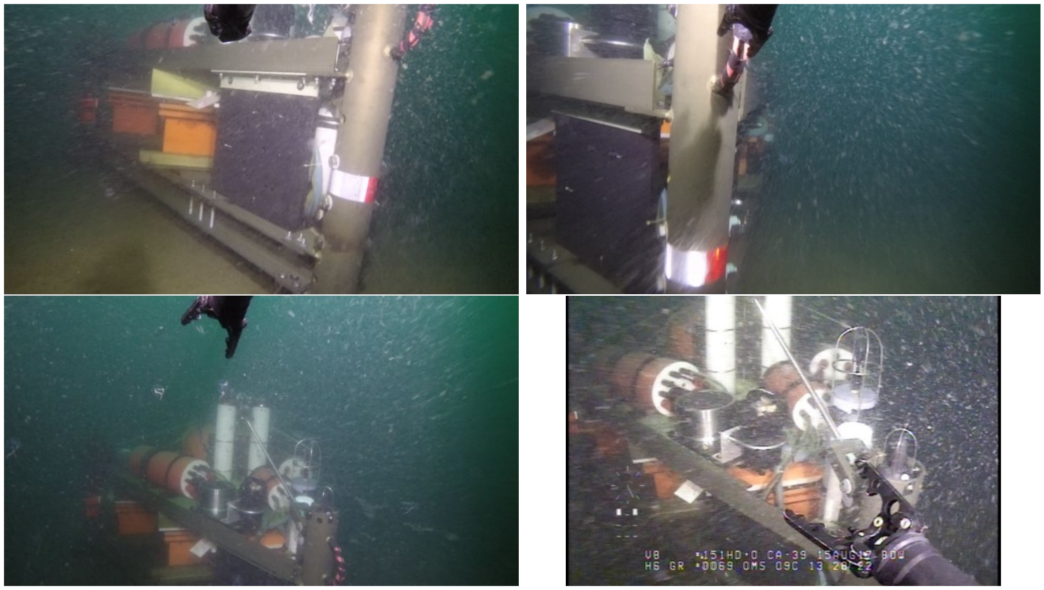


Figure 14. Images recorded by the AUV during inspection on the AutoAMP platform deployment at 60 m depth.

Accomplishments

Overall, these results and datasets demonstrate the feasibility and potential for semi-autonomous intervention in environments relevant to marine hydrokinetic arrays. The deployment in Newport Bay demonstrates time savings versus an unassisted operator who took 50% more time to grasp an 8 cm diameter handle in an environment typical of ocean current energy harvesting devices.

Conclusions

The offshore deployment of the AutoAMP platform demonstrates the potential for vehicles in deeper water environments (e.g., those typical of wave energy harvesting), but also illustrates a number of challenges. The vehicle's navigation system was less reliable in these scenarios, and ship support was difficult due to the requirement to move the ship as the tethered vehicle moved around in the underwater environment.

Recommendations

These results motivate further research into semi-autonomous navigation and manipulation in challenging marine environments capable of dealing with these issues.

References

[Lawrance et al., 2016] Lawrance, N., Somers, T., Jones, D., McCammon, S., and Hollinger, G. (2016). Ocean deployment and testing of a semi-autonomous underwater vehicle. In Proc. IEEE/MTS OCEANS Conference, Monterey, CA.