Post Access Interim Report

Wave Powered Oceanographic Gliders
Navigation Assessment

Awardee: Moye Consultants on behalf of
Team "Wave Powered Oceanographic Gliders"

Awardee point of contact: Davis George Moye
Facility: Sandia National Laboratories
Facility point of contact: Budi Gunawan

Date: June 21, 2024

TEAMER
Testing & Expertise for Marine Energy

EXECUTIVE SUMMARY

The goal of this project was to validate failed autonomous underwater vehicle (AUV) navigation and control systems, which were failed during an earlier study sponsored by the Dept of Energy's Ocean Observing Prize Challenge. The systems we sought to study were water-proofing/water-tightness of electronics enclosure and cable penetrations, simple dive/depth control, vertical profiling, underwater navigation, and satellite communications and navigation. Shipping delays cost one (1) of the two (2) weeks of scheduled testing. When testing began water-proofing/water-tightness proved to be a success. However, dive/depth control proved to be problematic on account of issues with the pressure depth sensor mechanism. These issues were solved, resulting in a successful dive/depth control test near the end of the end of the scheduled testing period. Work is underway to schedule a later testing period for vertical profiling, underwater navigation, and satellite communications and navigation.

1 Introduction to the project

The applicant is the Wave Powered Oceanographic Gliders team. We participated in and won prizes in the DISCOVER, DESIGN & BUILD stages of the DOE/NREL/PNNL/NOAA Ocean Observing Prize competition. The team is composed of two companies: Moye Consultants and Wave Venture. Moye Consultants' background expertise is in battery and supercapacitor energy storage systems and in oceanographic data collection and interpretation. Wave Venture's background is in offshore renewable energy in general and wave energy in particular.

Our project relates to our wave powered underwater glider (WPOG), and autonomous underwater vehicle (AUV) for oceanographic, climate science and bathymetric surveys. We are working to adapt wave energy to the blue economy application of AUVs. The first generation of the wave energy conversion subsystem within our AUV has been previously demonstrated and validated. We plan to use this TEAMER project to demonstrate our improved design for the depth control and underwater maneuvering of an AUV. Sandia National Laboratories' (Sandia) Lake facility is an ideal facility to undertake this validation testing. It has suitable size depth and lifting facilities to undertake the planned guidance, maneuvering and depth control tests.

The current project relates to our Ocean Observing Prize (OOP) entry. These prizes began with a concept design idea, then proceeded to verify and assess the concept and analysis conducted at each stage. Significant effort was put into the WPOG design. For the BUILD stage of the competition our team designed and built a wave powered autonomous underwater vehicle. Our wave powered AUV operates in two modes: generate and navigate. The wave energy generation performance of the system was demonstrated in wave tank testing in Plymouth University and in the MASK basin at the Naval Surface Warfare Center, Carderock, MD. During MASK basin testing we discovered that one of our cable penetration seals failed. This failure in the electronics housing prevented us from demonstrating the autonomous depth control and navigation system. We have since completed improvements to the electronics housing design.

The motivation for this TEAMER application is to firstly demonstrate that our improvements to the electronics enclosure are sufficient, and, secondly, to demonstrate the improved design of the control system for depth control and underwater maneuvering of an AUV. A successful testing program will position the WPOG one step closer towards commercialization.

More generally we are motivated to commercialize wave energy in blue economy applications and to use these as a stepping stone for the greater commercial maturity of wave energy.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

- Design a new version of our WPOG system, tailored to achieving the objectives in the RFTS8 proposal document. The new design will be tailored to be deliverable within the available time whilst also minimizing technology and project risks.
- Collaborate with SNL staff for advance planning of the testing at the SNL facility.
- Assemble a new system and undertake preliminary qualification testing to ensure hardware and software are ready for the test program. Preliminary prequalification testing will include submergence tests. (work performed by WV without SNL assistance prior to arrival at Lake Facility).
- Ship to SNL Lake Facility.
- Attend tests at the selected facility and lead execution of tests, in collaboration with SNL staff.
- Process and analyze data.

2.2 Network Facility Responsibilities and Tasks Performed

- Logistics and test planning: Sandia will discuss test requirements, logistics, paperwork with the recipient.
- Update work planning & control (PHS, NEPA, OP, JSA); Base & Sandia access paperwork: Sandia performs this task, with information from the recipient.
- Receive test article: Sandia receives the test article shipped by recipient. Article will be taken away by applicant after testing.
- Lake testing: Sandia staff were always present at the lake facility to help with the testing and to escort applicant visitors. Sandia staff were needed to escort foreign national applicant team members and designated lake facility staff were required to ensure safety procedures were followed during work.
- Applicant will perform the AUV testing (operation, ensure good data is collected). Sandia staff performed necessary work on the facility's side to ensure the AUV testing was completed successfully.
- Data post processing and analysis.

3 Project Objectives

OBJECTIVE 1

Demonstrate waterproof integrity of enclosures, cable penetrations etc.

In previous work a seal on a cable penetration failed, flooding control electronics, preventing demonstration of depth control and navigation functions.

Note: The preliminary visualization of the CAD model in Figure 1 and Figure 2 do not show the cable penetrations. There are two cable penetrations, both made with static penetrations with commercial-off-the-shelf (COTS) subconn connectors.

- From the electronics compartment to the thruster (9 core cable to the 3x 3 phase BLDC motors),
- From the electronics compartment to the buoyancy pumps (6 core cable, 2x 3 phase BLDC motors).

IMPROVEMENT:

Waterproofing electronics is necessary for WPOG function. These improved housing seals will enable future operations and testing. Our sealing approach will be improved through COTS cable penetrators designed for AUVs. Satisfying this objective overcomes a serious deficiency identified in a previous iteration of this technology.

OBJECTIVE 2

Demonstrate autonomous depth control.

The WPOG has an electronically controlled ballast system. We will first demonstrate Simple Dive / Depth Control and then a pre-programmed vertical profiling mission.

IMPROVEMENT:

The ballasting/depth control system controls depth and pitch and is essential to collecting data throughout the water column. As mentioned in the introduction we have not yet demonstrated the AUV's ability to dive and regulate depth. Validating our technologies ability to regulate depth will give confidence in the devices design and readiness for sea trials. Meeting this objective will confirm our technology can dive to specified depth(s) on demand. Furthermore, the intended horizontal travel method is underwater gliding and depth control is critical to this.

OBJECTIVE 3

Demonstrate autonomous navigation.

The wave powered AUV has thrusters and a solid state compass for underwater navigation. We will demonstrate simple navigation, including speed and heading control, while submerged.

IMPROVEMENT: Navigation is not yet demonstrated. These tests will evidence the AUV's ability to navigate. This is the primary requirement prior to sea testing and full autonomous integration.

Table 1. Intended outcomes and metrics

Outcome	**Related metric**
Water-proofing/Water-tightness of electronics enclosure and cable penetrations is demonstrated.	No water ingress No water damage to electronics systems
Simple Dive / Depth Control is demonstrated	System can execute a simple dive mission: dive 5 meters, hold constant depth for 5 minutes, resurface.
Vertical profiling is demonstrated	System can execute a simple vertical profile mission: dive to 5 meters and resurface again in steps 0.5m. Hold each step at constant depth for 1 minute.
Underwater navigation is demonstrated	System can control direction heading while submerged. System can control forward speed while submerged.
Use of satellite communications & GPS are demonstrated	System can send and receive data while on land System can send and receive data while surfaced in the lake. System can get GPS fixed while on land. System can get GPS fix while surfaced in the lake.

4 Test Facility, Equipment, Software, and Technical Expertise

The Lake Facility is suitable to achieving the applicant's objectives, mainly because of the large size of the tank. The Sandia Lake Facility's outer surface footprint is a 57.3 m by 36.6 m water tank, with a 15.2 m water depth. The sidewalls of the basin are angled at approximately 45 degrees.

There are two I-beams secured to the bottom face which provide anchor points.

The facility's current overhead lifting capability is 1,361 kg (3,000 lbs); however, since it is located outdoors, it has the advantage of being easily accessible by additional cranes for lifting larger loads. The facility offers four certified divers and technician support. A 208 volt, 3 phase, 100 amp power source is available on-site. In addition, several 100-150 kW portable generators are available at Sandia to be brought to the facility as well. Furthermore, as part of Sandia, the facility is DOE property. The actual AUV under test is only 30 kg (66 lbs).

The TEAMER project using the facility will benefit from faster work planning and control processes (e.g. primary hazard screening (PHS), NEPA compliance, operating plan (OP) preparation, job safety analysis (JSA), safety case (SC), safety assessment (SA)), and can leverage previous work funded under the WPTO Lake Facility upgrade project for streamlining this process.

A further advantage of the Lake Facility over other testing tanks is that the Lake Facility is outdoors while most other wave tanks are indoors. The Lake Facility will enable better reception of GPS and satellite communications signals, which will allow these components to also be tested.

- The Lake Facility has the required water depth and length/width for the proposed tests.
- The Lake Facility has adequate lifting capabilities for the test unit.
- The Lake Facility has no roof, eliminating a potential source of interference during our satellite communications and GPS tests.
- Sandia's Water Power Technologies Department, as well as the Robotics Department, have significant experience in wave energy and AUV design & testing.
- Sandia received a Phase 1 FY22 Seedling funding for the project entitled "Autonomous ADCP deployment using a low-cost AUV to improve personnel safety, reduce measurements cost and simplify measurements over multiple locations." The project plans to utilize the Lake Facility for AUV testing in Phase 2.
- Sandia is a major DOE Engineering Lab with 15,000 staff, of which more than 50% have engineering backgrounds. This provides capabilities to solve multidisciplinary engineering problems, including hydrodynamics, structural, electrical, and mechanical, as well as engineering operations, verification, and validation.

5 Test or Analysis Article Description

Figure 1 and Figure 2 show the minimal assembly, composing only the subsystems that we plan to test in the TEAMER project. This minimal assembly is approximately equivalent to the compute, communications, control sensing and actuation equipment in one of the flaps of the whole system, but without the generator. The background to this work is participation in the Ocean Observing Prize competition. One of the lessons learned in that effort has been that the scope of the full system and planned tests was too wide to be completed with the available resources. The rationale for testing a reduced subset of the full system is risk management. Testing a lower number of subsystems and a physically smaller device makes development and testing with available resources feasible and lower risk.

Therefore, for this project we did not test a full WPOG, including wave energy generation components, but only a minimal system to demonstrate the failed control components. This includes the electronics enclosure, complete with minimum external hardware for communications, depth control, and propulsion. Understandably, results are different than would be expected, had we attempted to mimic the shape, mass and other dynamic properties of the whole system in these tests. Instead, the test device is housed in a simplified chassis based on v-slot extrusions and tubular enclosures. The planned tests still address the targeted objectives. The results will be transferrable to the larger system in terms of design methods, mechanical electrical and electronic hardware selection, software structure, analysis methods, and project management, even if some coefficients must be re-acquired at a later date for the larger system. Note that in any case the properties of the larger system are not finalized and are subject to change. This is another rationale for our testing a reduced system.

The subsystems included are:

- Electronics and battery enclosure
- Buoyancy engines
- Main thruster
- Bow thruster

The test article's approximate dimensions are:

- 1,500 mm long,
- 220 mm wide,
- 200 mm high.
- ≈30 kg weight

Data will be collected by the on board microcontroller system, stored on a SD card and uploaded via Iridium satellite (or recovered directly from the SD card after the tests). The tests will advance the applicants understanding of navigation and depth control systems.

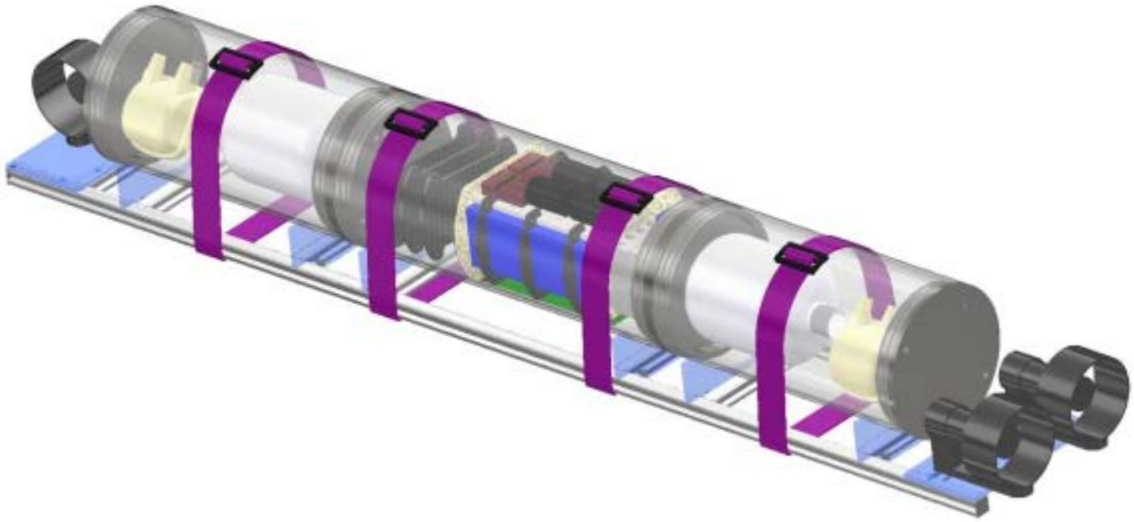

Figure 1. Test article, isometric view.

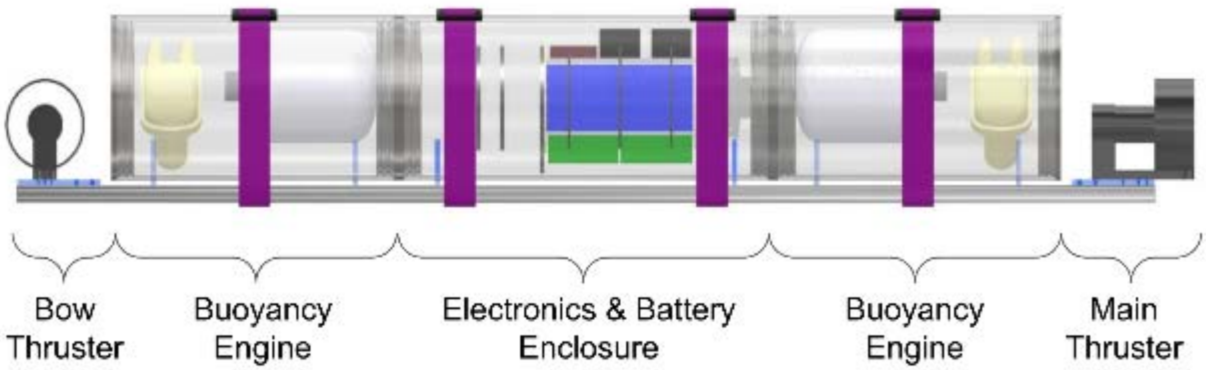

Figure 2. Test article, side view.

6 Work Plan

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

The following tables give details of the variables will be recorded by the onboard micro-controller and the instruments used. The onboard microcontroller will be an ARM Cortex M7.

Table 2: List of Instrumentation Equipment:

Navigation:		
Quantity Measured	**Component Manufacturer and Part Number**	**Location**
GPS location (when surfaced)	UBLOX SARA-R5	Electronics and Battery Enclosure
Compass Heading	Bosch BNO055	Electronics and Battery Enclosure
Pitch angle	Bosch BNO055	Electronics and Battery Enclosure
Roll angle	Bosch BNO055	Electronics and Battery Enclosure
Depth	Unbranded automotive pressure sensor	Electronics and Battery Enclosure
Raw IMU readings 9 axis accelerometer/gyroscope/magnetometer	Bosch BNO055	Electronics and Battery Enclosure
Environmental:		
Quantity Measured	**Instrument Manufacturer and Part Number**	**Location**
Water temperature	Dallas Semiconductor DS18B20	Electronics and Battery Enclosure
Equipment Status:		
Quantity Measured	**Instrument Manufacturer and Part Number**	**Location**
Battery voltage and current	Texas Instruments INA260	Electronics and Battery Enclosure
Microcontroller % processor load (or a suitable proxy for this)	Software	Electronics and Battery Enclosure
GPS signal strength (when surfaced)	UBLOX SARA-R5	Electronics and Battery Enclosure
Comms signal strength (when surfaced)	Iridium 9603N	Electronics and Battery Enclosure
Enclosure internal temperature/pressure/humidity	BOSCH BME280	Electronics and Battery Enclosure
Water ingress detection	Bespoke in house sensor design	Electronics and Battery Enclosure

Imaging for Motion Tracking Data

Imaging will be utilized to measure the motion of the test unit and provide data to validate against the on-board data. Detailed imaging parameters, camera configurations, and data products are provided in the attached Photometrics Test Plan.

6.2 Numerical Model Description

Not applicable.

6.3 Test and Analysis Matrix and Schedule

■ 6.2.1 PRE-QUALIFICATION TESTS

Prior to the onsite TEAMER tests all subsystems were tested thoroughly. Particular attention was paid to waterproofing the electronics housing and its cable penetrations and connectors. Test results will be shared with SNL prior to shipping the test article. Initial meeting with Sandia's SMEs took place earlier in the year. Additional meetings were planned for early 2024 prior to the testing and during the week prior to testing.

Pre-qualification tests included:

- Water-tightness test - external pressurization - water medium – 0.5 m immersion
- Test water ingress sensor
- Test depth sensor
- Test solid state compass / IMU
- Test buoyancy engine control
- Test thruster control
- Test GPS system
- Test satellite communications
- Measure mass of device
- Measure mass moments of inertia in yaw and pitch (pendulum method)

6.2.2 LAKE TEST SCHEDULE

Table 3: Work schedule.

Notional Period		Activity	Lead
Week 1	Mon	Check in, facility clearance, and Lake Facility safety and planning discussions	Facility
Week 1	Tues-Fri AM	Applicant down, awaiting system delivery	Applicant
Week 1	Tues-Fri AM	Photometrics system prepared at lake facility	Facility
Week 1	Fri PM	Unbox & set AUV up for tests.	Applicant
Week 1	Sat	Set AUV up for tests and pretest systems outside of lake facility. Perform depth calibrations in offsite pool.	Applicant

Week 2	Sun	Set AUV up for tests and pretest systems outside of lake facility. Perform depth calibrations in offsite pool.	Applicant
Week 2	Mon AM	Demonstrate satellite communications & GPS reception on land	Applicant
Week 2	Mon PM	Final safety brief	Facility
Week 2	Mon PM	Water-tightness test – water medium - external pressurization - 0.5 m immersion. This will achieve outcome Water-proofing/Water-tightness.	Applicant
Week 2	Mon PM	Performed three (3) 1 m depth tests (unit to submerge, dive and hold at 1 meter). System failed to maintain neutral buoyancy, although good communications and unit interaction. The 2nd test was not able to be flashed with the modifications needed, but possibly identified the heat caused issues (equipment may have overheated). Test 3 showed great improvement to dive control and some improvements to pitch control. Determined that inertial measurement units (IMU) failing to automatically calibrate and giving bogus answers to inclinometer. The end of the day was then determined; to allow the customer to review test logs and make more appropriate changes. Further depth test will still need to be conducted.	Facility
Week 2	Tues AM	Further efforts to equalize and calibrate pressure sensors inside device and to calibrate device to maintain level pitch and neutral buoyancy	Applicant

Week 2	Tues PM	Successful sensor tests performed; Sensors able to be calibrated while also some equipment changes made. After the sensor testing a depth test was conducted with the full unit. With some additional modifications to photo and unit weight (adjust buoyancy and balance of unit), unit was submerged 1 m, followed by 2 m, then back to 1 m. Depth sensor test proved successful. Key interim milestone needed for project success	Applicant
Week 2	Weds	Updates made to control algorithms to maintain neutral pitch and buoyancy underwater	Applicant
Week 2	Weds	Observing holiday	Facility
Week 2	Thurs	Continuing to adjust control algorithms; During this time aft controller repeater was damaged by overvoltage, pausing testing	Applicant
Week 2	Fri	Demobilization and packing	Applicant

6.4 Safety

Sandia provided the applicant relevant safety documents for testing at the lake. Applicant familiarized its staff with documents, including Safety Case, Primary Hazard Screening (PHS), Job Safety Analysis (JSA), Operating Procedure (OP). The applicant and the facility will hold an online Q&A session on the safety documents and procedures. During the testing campaign the team performed daily safety briefings, reviewing potential hazards, risks, and mitigation procedures, as well as any PPE required. Sandia created a log file was created to record these meetings and the lake activities conducted each day.

6.5 Contingency Plans

The following possible risks and impact to the test campaign are carried over directly from the Test Plan:

Risk	Mitigation
Poor weather conditions leading to the test campaign to be postponed	• Sandia will do their best to reschedule the testing to future dates.
Test article system or component failure	• System and subsystems will be tested in full and at component level prior to main Sandia tests. • System will arrive fully assembled - reducing assembly risk • Range of components will be brought as spares should there be a component failure during testing.
Camera system is unsuitable or doesn't work properly	• Camera system will be calibrated and tested prior to the project start date. We are using standard methods we regularly use for our large scale tests so we do not anticipate any issues with the imaging system.
Test article not ready or problems happen in pre-qualification tests	• Discussions around the flexibility on lake usage if contingency time is needed have been had and Sandia has agreed that it is possible.
Problems with device performance not identified while tests are ongoing	• Between tests review data (as feasible) to assess test success (or failure) While team is still on site so tests can be repeated as necessary.

The largest issue faced was, "Test article not ready or problems happen in pre-qualification tests." Applicant requested Facility authorize overtime to perform lake facility testing over weekend, but this was not authorized. AUV arrived during Week 1, Friday AM, and was available for unpackaging Friday PM. Consequently, Applicant took test article AUV offsite to work on it over the weekend and to perform initial setup and to verify watertight integrity so that remaining time at lake facility could be maximized.

We discovered that pressure depth-sensing is a tricky depth measurement method. Survey markers near the Lake Facility indicated the altitude was 5,400 ft (1650 m) above sea level. Developing an accurately calibrated pressure-depth sensing method proved to be a challenge, which was eventually solved by a means of opening and closing the AUV's sealed components immediately prior to deployment and by modifying the AUV to equalize atmospheric pressure in the forward and aft compartments.

6.6 Data Management, Processing, and Analysis

6.6.1 Data Management

Data collected within the AUV was stored locally on a SD card and was downloaded and stored to a field laptop and cloud service for backup. Data collected by Sandia (e.g. the video camera recordings) was copied to a project folder within Sandia's collaborative space, which is automatically backed up by the Sandia IT system every night. Raw and processed data was curated prior to submission to MHK DR in the .CSV and .NPY data formats, including metadata. Proprietary data is identified. We requested a 5 years protection of this proprietary data under the terms of the DOE award.

6.6.2 Data Processing

Performance data was directly sent to an operational laptop via a tether. Dive depths were never deep enough to merit a SD card and device disassembly between dives.

Additionally, Sandia staff provided high definition video services. During dives a pair of high capture rate, high definition GoPro cameras were mounted to the AUV's bow and stern, respectively. Given the modifications made to the test plan, this data mostly focused upon ensuring accurate depth sensing and controls to dive and then to achieve neutral buoyancy.

Error Estimation

Error estimation was facilitated by comparison of the commanded setpoint trajectory with 2 or more estimates for device position in relevant degrees of freedom. In particular our study made the following comparisons for each test:

Depth comparison:

- Depth sensor readings
- Z values from the motion tracking
- Depth setpoint

Pitch comparison:

- Pitch value derived from depth sensors
- Inclinometer value from IMU
- Pitch value from optical motion tracking
- Pitch setpoint

And our study had planned to make the following, additional comparisons, which were omitted due to the shortened test period. We intend to perform these measurements during the final test.

Yaw comparison:

- Yaw value from solid state compass
- Yaw value from optical motion tracking
- Yaw setpoint

Horizontal X, Y position:

- X & Y values from optical motion tracking
- X & Y values derived from combination of IMU and speed sensor

6.6.3 Data Analysis

Depth control and navigation system:

For the depth, heading and pitch control the data as analyzed to determine the following quantities:

- Time constant in step response
- Error band
- Absence of overshoot
- Absence of oscillation

The navigation tests were not performed, due to the shortened test period. During the final test data will be analyzed to determine the following quantities:

- Time constant of forward speed in step response
- Stability in heading and depth control while under forward speed
- Error band in heading and depth control while under forward speed
- Accuracy of waypoint navigation

Dynamic system

Sufficient data was not collected from the tests to fit a dynamic model to the data. After the final test we hope to fit a dynamic model to the data to better understand the properties of the device and to gain experience of the fitting procedure so that it can also be applied to future vehicles.

In particular we will attempt to extracting the following characteristics from the recorded data:

- yaw drag coefficient
- yaw added mass coefficient

- yaw moment curve (Pulse width modulation % -> Nm)
- forward drag coefficient
- forward added mass coefficient
- forward thrust curve (Pulse width modulation % -> N)

Together with the measured mass properties the above data will allow us to populate a dynamic model of the system.

While the dynamic system of the test article is significantly different form the eventual commercial system (e.g. different mass, geometry) the experience and methodology of fitting a dynamic model to the results will be reusable with future devices. Completing this step will be valuable in developing methodologies for tuning control systems for those future devices and will facilitate the objectives of improved depth control and navigation.

Underwater imaging for motion tracking

As discussed in Photometrics Test Plan, x-y imaging measurements will be provided for the translation tests and x-z imaging measurements will be provided for the depth tests as a function of time. Data will be provided in a CSV file as a function of time. The final Photometrics Test Report will include uncertainties for the measured data.

7 Project Outcomes

1. Results

The targeted project objectives and outcomes have all been achieved. Access to TEAMER facilities and processing of lessons learned in the process of the TEAMER project have been instrumental in achieving this. Some of the targeted objectives and outcomes were achieved within the timeframe of the testing scheduled at the TEAMER test facility while other objectives and outcomes were achieved after processing lessons learned.

2. Review of Objectives

OBJECTIVE 1: This objective relates to waterproofing of various cable penetrations on the electronics enclosures used in the project. The background to this requirement is that in previous testing, prior to TEAMER, a cable penetration failed. Therefore, the primary objective in this project was to demonstrate improved design and execution of these penetrations. Two types of cable penetrations were used in the project. These were a) off the shelf MacArtney subconn series connectors and b) in house potted cable penetrations using an improved procedure.

The MacArtney connectors were used for connecting the two electronics enclosures together and for connecting the external thruster motors to the electronics enclosure. The in-house potted penetrators were used for comms cables, USB and RS485. Three potted connectors were made, one for USB, one for RS485 and a third with both USB and RS485.

All of these approaches worked well and OBJECTIVE 1 was achieved in full. Lessons learned in relation to these connectors are given in section 7.2.

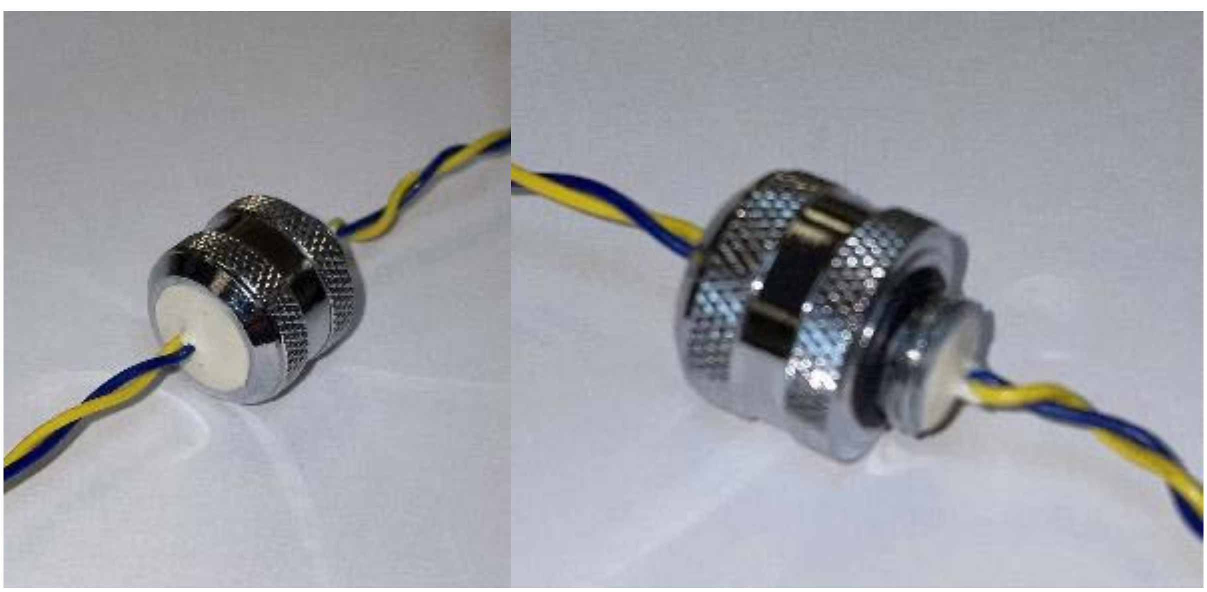

Figure 3. RS485 cable penetration. The cable is potted into an off the shelf plumbing fitting with G1/4" thread and o-ring seal. See section 7.2 for further details.

Figure 4. Combined USB (white/green) and RS485 (blue/yellow) cable penetration. The cable is potted into an off the shelf plumbing fitting with G1/4” thread and o-ring seal. See section 7.2 for further details.

Figure 5. Picture of the G1/4” plumbing fitting used for cable penetrations. Left: external G1/4” thread with o-ring seal. Right: Internal grooves. The fitting is sold for liquid cooled computers. See section 7.2 for further details.

Figure 6. View of electronics enclosure assembly showing tube end cap with all connectors in place. Centre is the McArtney bulkhead connector. Top is a USB penetrator made in the same way as is shown in Figure 3 to Figure 5. Bottom is the McArtney connector for the thruster motors.

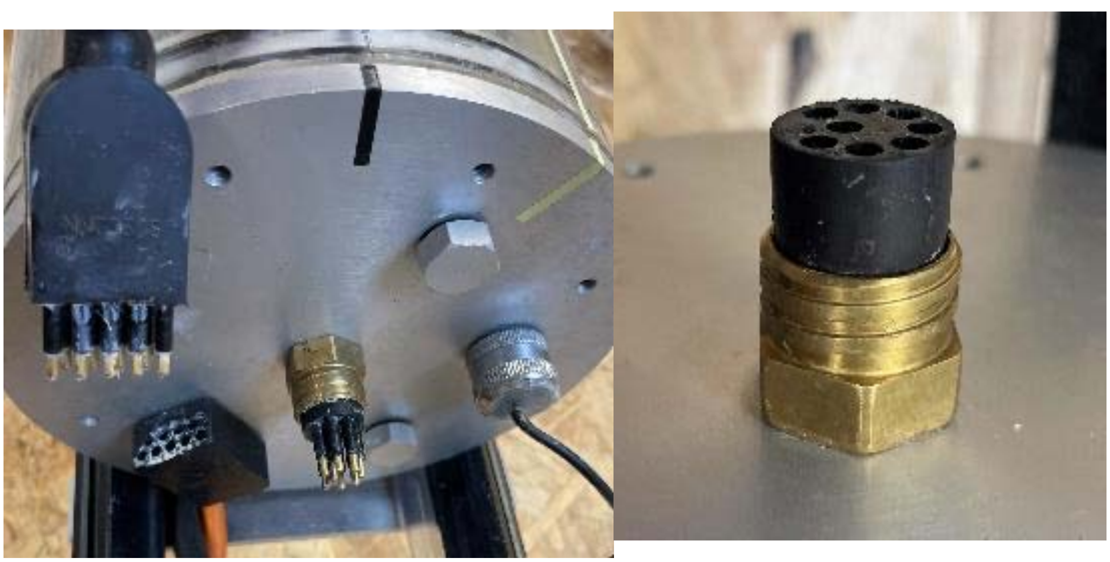

Figure 7. Electronics enclosure assembly showing Mcartney connectors opened.

OBJECTIVE 2: Demonstrate autonomous depth control. Depth control had been demonstrated in pre-qualification testing before the onsite work in the TEAMER test location. In the TEAMER testing several issues arose in relation to both depth sensing and depth control. These issues arose due to differences between the test conditions in the pre-qualification tests and in the TEAMER test location. These are fully detailed in section 7.2. In brief the differences between pre-qualification test conditions and TEAMER test conditions are:

> Altitude: Pre-qualification tests were conducted close to sea level while the test location in Albuquerque is approximately 1500m above sea level. This caused some issues that were time-consuming to diagnose but easy to resolve once understood.
>
> Environmental: Pre-qualification testing was conducted in an indoor tank so that temperature fluctuations were minimal while TEAMER testing was conducted outdoors in strong sunlight. Temperature changes and solar heating of the test unit caused issues that were again time-consuming to diagnose but easy to resolve once understood.
>
> Handling: During pre-qualification testing the test article was placed in the water by the same team that developed the unit while during TEAMER testing the unit was placed in the water by SNL staff. In the pre-qualification test tank was 'laboratory conditions' with repeatable initial condition for each test while the SNL lake was closer to 'real world conditions' with higher variability in placement of test unit and increased environmental disturbances.

TEAMER testing was invaluable in identifying these issues. After the issues raised by these differences were addressed, autonomous depth control was demonstrated. However, due to the time required for software changes this demonstration was done after TEAMER testing was over and at a different location.

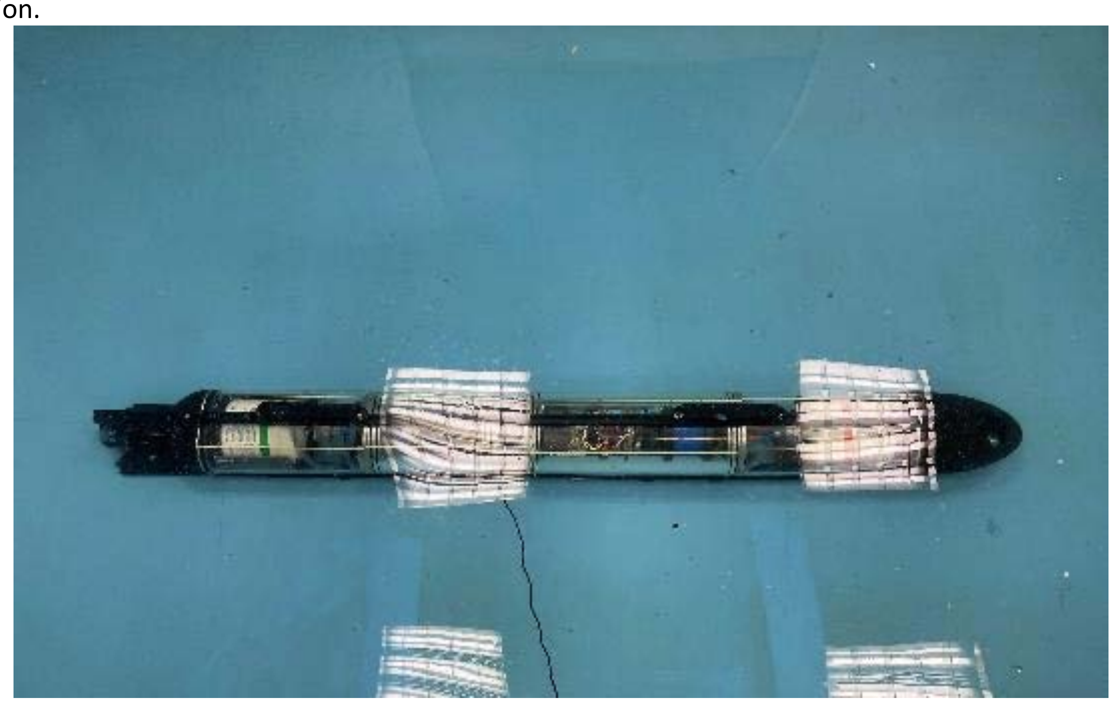

Figure 8: In-house depth control test post TEAMER.

OBJECTIVE 3: Demonstrate autonomous navigation:

This objective was achieved. Since this objective was contingent on functioning depth control this objective was achieved after the TEAMER testing at a different location.

The navigation tests depend on yaw control and depth control. Initial depth and yaw control tests were done in the in house tank shown in Figure 8. The navigation tests were done in a local boating lake near the Wave Venture offices at Hoylake RNLI near Liverpool Uk, see Figure 9 to Figure 10.

Navigation tests were conducted both submerged and surfaced. The surfaced tests allowed GPS tracking while the submerged tests did not. Submerged tests were verified visually.

Figure 9: Navigation and maneuvering tests post TEAMER were done at Hoylake RNLI boating lake. The lake is approximately 30m x 33m.

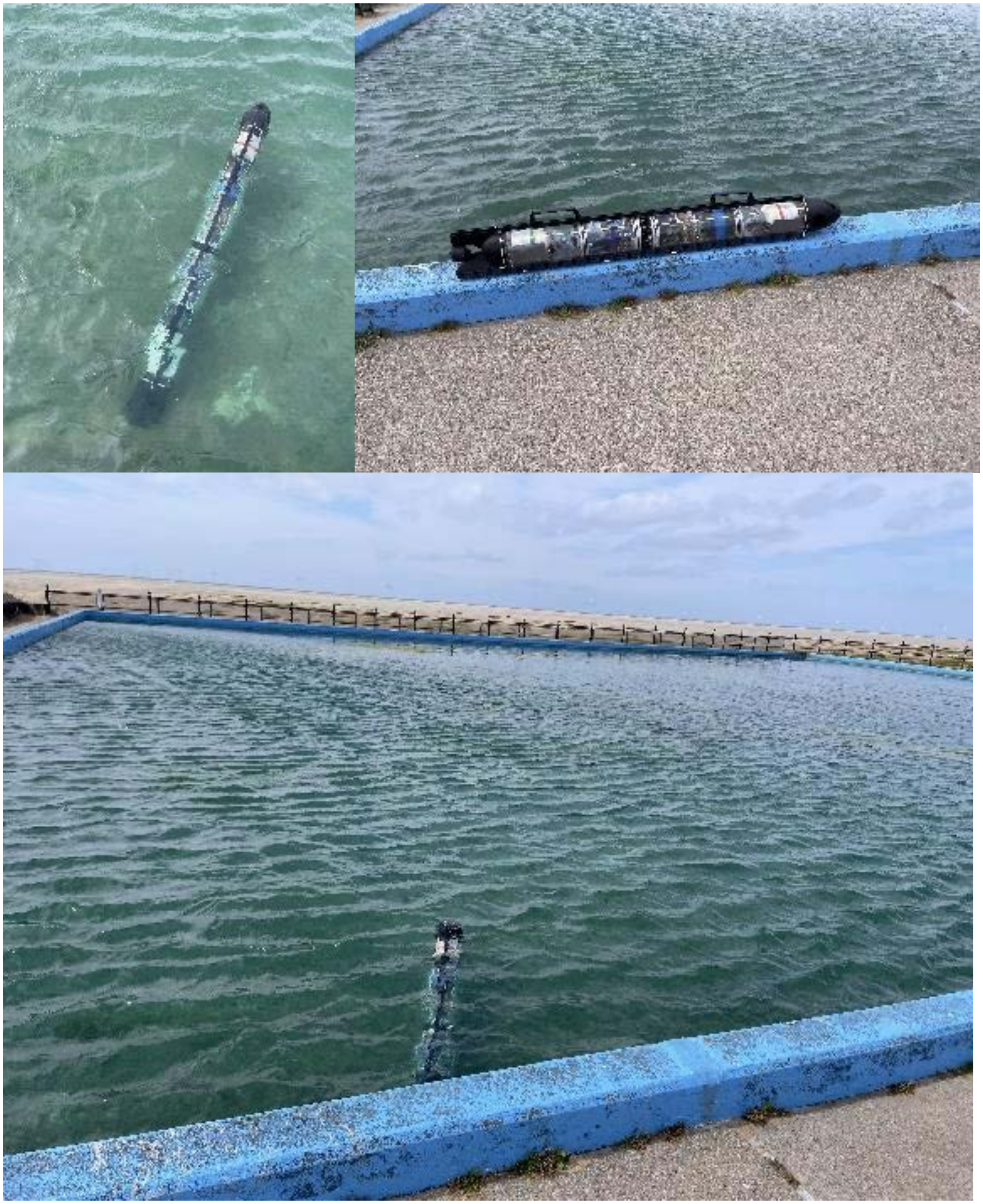

Figure 10: Navigation and maneuvering tests. Top left submerged; Top right drying out after test; Bottom test start position.

3. Review of Outcomes

Table 2 gives a review of the targetted outcomes which were stated in the project proposal and also presented above in Table 1. The comment column gives a summary of how/when the outcomes was achieved.

Table 2. Intended outcomes and metrics

Outcome	Related metric	Comment
Water-proofing/Water-tightness of electronics enclosure and cable penetrations is demonstrated.	No water ingress No water damage to electronics systems	Achieved
Simple Dive / Depth Control is demonstrated	System can execute a simple dive mission: dive 5 meters, hold constant depth for 5 minutes, resurface.	Achieved after TEAMER testing timeframe, using lessons learned in TEAMER. (Depth of final test was less than initially targeted)
Vertical profiling is demonstrated	System can execute a simple vertical profile mission: dive to 5 meters and resurface again in steps 0.5m. Hold each step at constant depth for 1 minute.	Achieved after TEAMER testing timeframe, using lessons learned in TEAMER. (Depth of final test was less than initially targeted)
Underwater navigation is demonstrated	System can control direction heading while submerged. System can control forward speed while submerged.	Achieved after TEAMER testing timeframe.
Use of satellite communications & GPS are demonstrated	System can send and receive data while on land System can send and receive data while surfaced in the lake. System can get GPS fixed while on land. System can get GPS fix while surfaced in the lake.	Achieved

7.1.1 Depth Control Results

Lessons learned in the depth control testing within the TEAMER tests are discussed in section 7.1.4. Figure 11 shows a result from a successful test completed after the TEAMER access. The overall buoyancy control was tweaked to give higher priority to pitch control than depth control, the response time of the depth control was increased (slowed down). When the magnitude of pitch error is greater than 1° depth control is paused and the controller operates on pitch only until the magnitude of pitch error is less than 0.85° again.
This approach might not be needed when operating well below the water surface but for overcoming the difficulty of pitch instability in the initial submergence this strategy was very successful.

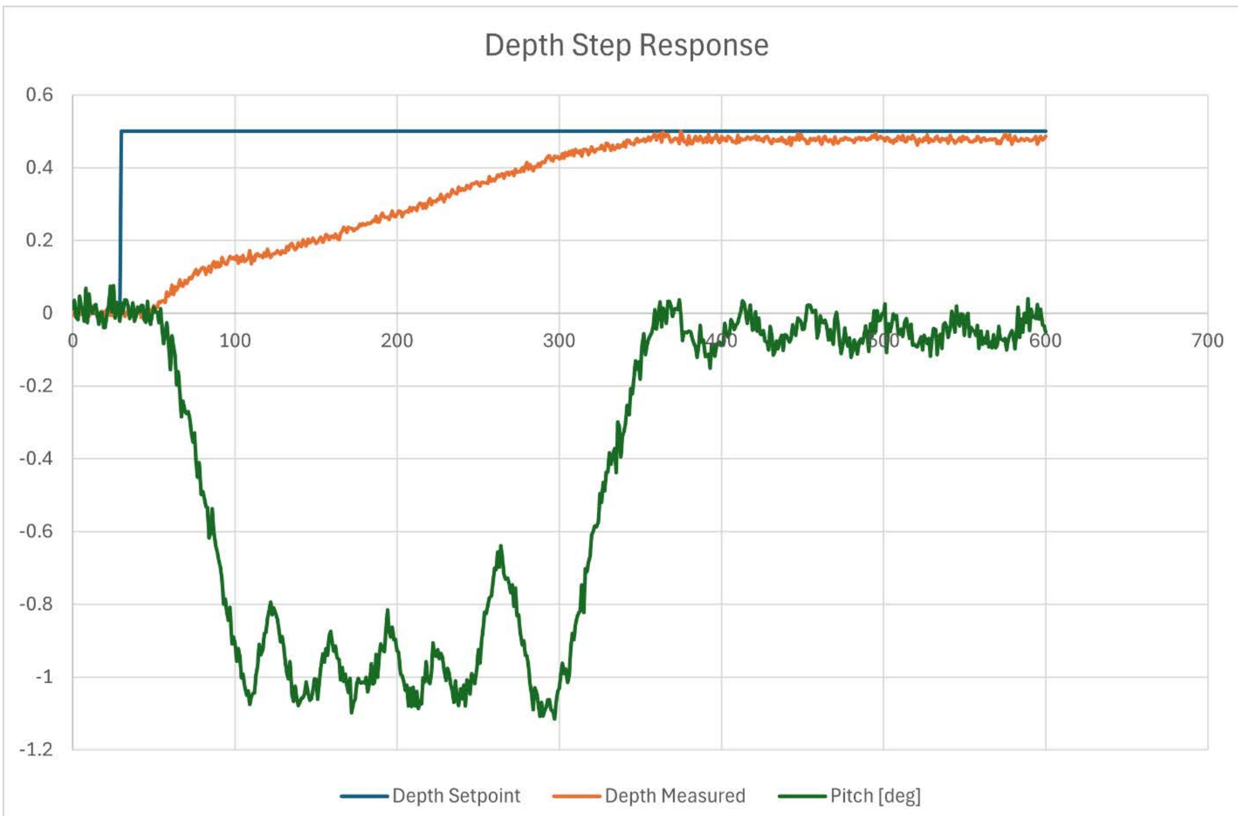

Figure 11. Depth control test with combined Pitch and Depth objectives.

7.1.2 Yaw Control Results

Figure 12 shows the results of a yaw step response test. Continuously running the thrusters with RPM controlled by PID controller was found to drain the batteries very quickly an alternative strategy with pulsed use of the thruster was adopted. The controller calculates the RPM needed and the pulse duration for each pulse, after the pulse is executed, a lockout is enforced to prevent another pulse for a period. Pulse durations were a minimum of 3 seconds and a maximum of 5 seconds, the lockout duration was 20 seconds. A deadband of 5° is also enforced so no pulses are executed when the error magnitude is less than this threshold. This strategy was stable and gve significantly lower energy usage for acceptable results.

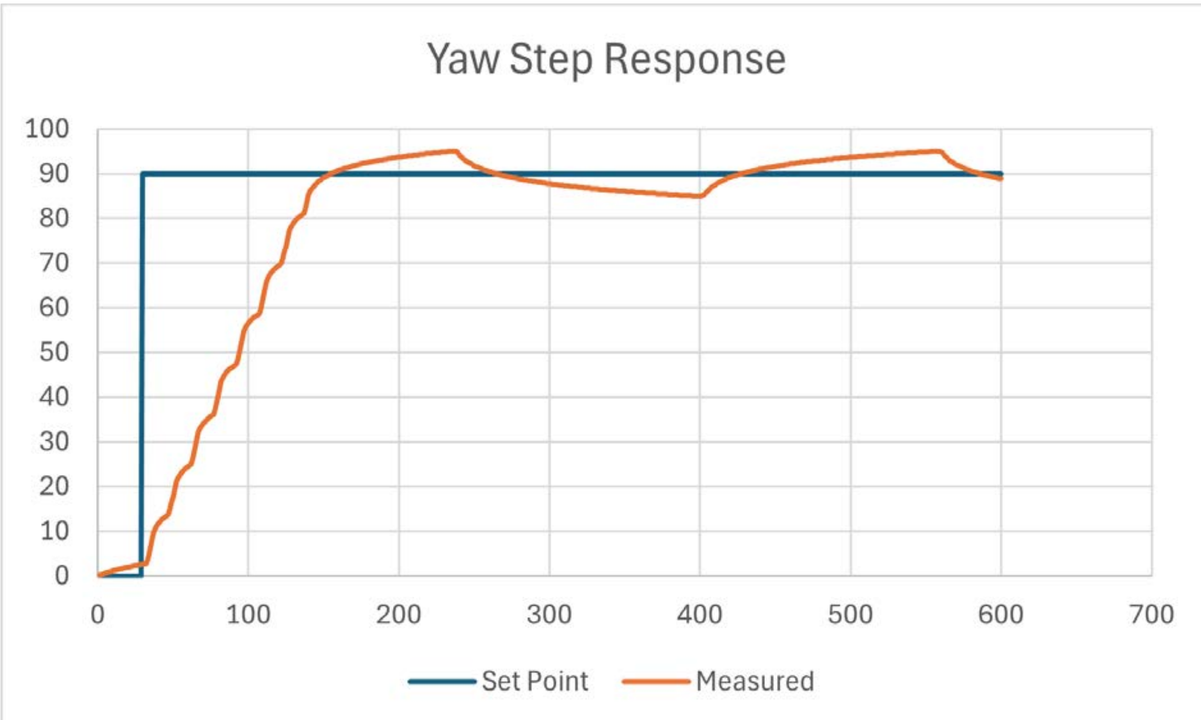

Figure 12 Yaw step response.

4. Lesson Learned and Test Plan Deviation

7.1.3 Project Planning

The test article arrived late to the test facility. There were a number of factors which led to this, UPS estimated shipping times turned out to be wildly optimistic. The process was complicated by the presence of lithium-ion batteries and steel pressure vessels in the vehicle design. About 4 days testing was lost due to these delays.

The lessons learned are:

- When shipping by airfreight, then source batteries and pressure tanks locally at the destination and avoid shipping these items. This also applies to any other items that might be classed as dangerous cargo.

- Consider transporting as many subsystems as possible in airline luggage rather than shipping.

7.1.4 Testing Procedures

Delays in test article delivery cut short available test time. Consequently, we modified the test plan to move repeat tests to the end of the test session and reprioritized them as optional, time tasks, time permitting. The purpose of this was to maximize our ability to complete all tests at least once, rather than to risk not completing a task in exchange for the nominal benefit of a redundant test.

7.1.5 GPS - IMU – Satellite Communications

We successfully demonstrated satellite communications on land.
We successfully demonstrated GPS reception on land.
We successfully calibrated the IMU sensor by following the manufacturer's instructions for Magnetometer, Accelerometer, Gyroscope and saved the calibration vectors in the controllers EPROM.

7.1.6 Depth Sensors & Depth Control

Several issues were discovered that impacted on the depth sensors and depth control. These were all related to differences between test conditions at the TEAMER test site at SNL compared to the pre-qualification test location.

The buoyancy tanks used in the test article are steel tanks with a rubber diaphragm that seals the gas volume inside the tank. In operation, this gas is compressed by water that is pumped into the tank. The TEAMER location is approximately 1500m higher altitude compared to the pre-qualification test location. This resulted in an overpressure in the internal gas (which was filled at sea level) relative to the atmospheric pressure at the test site. This resulted in the buoyancy pumps appearing to draw more current and to reach their stall current/torque at a lower tank filling level.

The higher currents were noted. Diagnosing this took over a day of test time. Once the problem was understood, the gas pressure was reduced and the motor currents returned to the expected values.

A second issue occurred with the forward and aft depth sensors appearing to deviate from their previous calibration offsets resulting in these sensors measuring different depths even when the vehicle was level. The problem was eventually attributed to solar heating / solar gain of the test unit which impacted the forward and aft enclosures differently. While both enclosures received equal heating, the forward enclosure was frequently opened to connect various USB cables, and to charge the batteries, on the other hand the aft enclosure was much less frequently opened. As a result, the pressure in the forward enclosure was close to atmospheric pressure before each test, while the pressure in the aft enclosure was above atmospheric pressure due to heating of the closed volume. This difference in the internal pressures impacted the depth measurements.

We considered adding a tube connecting the two enclosures to guarantee equal pressure in each. However, this would undermine the rationale for having two enclosures which is to isolate the pumps in a separate enclosure to the battery and main electronics. Ultimately this problem was overcome by adding a step in the test procedure to vent the enclosures at the start of each test to ensure that both enclosures start at atmospheric pressure. This problem was time-consuming to diagnose but once understood it was easy to overcome.

A further issue was lack of robustness in the depth controller to the initial conditions of each test. In the pre-qualifications tests, the initial conditions of each test happened to be very consistent. This was not especially by design; it happened that the roll, and pitch were always close to zero and that the vehicle and the water were relatively still. In the TEAMER tests the initial conditions were more varied, closer to real world conditions, and the environment was not as static. It emerged that the depth control was sensitive to initial nonzero pitch and to movement while the vehicle was surfaced. In combination with the already mentioned issues with depth sensors this meant that the depth and pitch control was not demonstrated during the TEAMER tests. After the TEAMER tests the pitch and depth controllers were retuned and the issues with the depth sensors were overcome. The depth control was demonstrated subsequently.

8 Conclusions and Recommendations

Obvious necessary improvements include the test planning matters previously discussed in **7.4.1** Specifically, care should be taken to ensure potentially hazardous components are shipped separately from the entire test article and arrangements are made to procure components near the test site, if necessary.

The next most important lesson to date is the necessity of maintaining a flexible test plan. By doing as we did in having the test plan segmented, it is easy to accomplish preliminary tests and to abbreviate and possibly resume tests.

The TEAMER testing produced valuable insights and experience.

Some of the project objectives were achieved within the timescale of the TEAMER testing schedule.

The remaining project objectives were achieved after the TEAMER testing once the lessons learned were processed.

9 References

No outside references are included for this report.

10 Acknowledgements

This work was funded by the Testing & Expertise for Marine Energy (TEAMER) Network RFTS 8.

11 Appendix

None.