DESIGN AND PERFORMANCE OF ODYSSEY IV: A DEEP OCEAN HOVER-CAPABLE AUV

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Abstract

The Odyssey IV class AUV was designed to fill the evolving needs of research and industry for a deep rated (6000 meter) vehicle, which is capable of both efficient cruising and precise hovering. This AUV is powerful enough to reject currents typical in the open ocean environment and yet small enough to be deployed from a small fishing boat. The thruster layout, two vectored side thrusters and two fixed cross-body thrusters, allow for 4-DOF control which gives this vehicle precision and flexibility not possible in previous Odyssey class AUVs. An adaptable payload area allows the mounting of sensors, actuators, or other hardware suitable to a particular mission. The dynamic control layer of our behavior-based MOOS software was completely redesigned to take advantage of the capabilities of this vehicle. This is also the first platform to utilize new graphical controls and database-driven logging which increase operator efficiency and make the vehicle safer to operate. Odyssey IV's intended uses include survey and inspection of cold water corals, fisheries, archaeological sites, and subsea infrastructure. It will also serve as a research platform for computer vision-based servoing and acoustic supervisory control. This paper will document the design considerations and implementation of the Odyssey IV, as well as report on a series of field tests culminating in its first scientific deployment at Georges Bank, observing and mapping the invasive tunicate Didemnum.

Introduction

The Odyssey class AUVs, typical of those designed by the AUV Lab at MIT Sea Grant, has been "torpedo" or "cruising" style vehicles. This type of vehicle will usually have a preferred streamlined horizontal axis along which it can cruise efficiently. These vehicles are excellent for survey missions requiring long distance horizontal travel. The cruising AUV is typically propelled by a rear propeller and controlled through a set of actuated rudder and elevator fins, which provide control over the yaw and pitch axes respectively. For over 10 years, Odyssey II vehicles have run successful surveying missions gathering data under arctic ice,[1] collecting sonar and image data of fisheries habitat, [2] and collecting chemical spectroscopy data in lake environments.[3]

Though cruising style vehicles have their advantages, namely improved speed and battery life through hydrodynamic efficiency, they also have limitations. Cruising AUVs have a minimum controllable speed, below which the tail fins cannot generate sufficient lift. Also, a cruising vehicle's degrees of freedom of motion tend to be limited to surge, pitch and yaw. This makes close-up, detailed inspection of some object of interest very difficult because the target is only in the field of view briefly as the vehicle passes over. The cruising AUV has no ability to stop or sway sideways over the object, it must circle around for another pass.

On the other end of the vehicle design spectrum is a hovering vehicle. Starting in 2003, the AUV Lab and Bluefin Robotics collaborated to develop a hovering AUV or HAUV.[4] This vehicle achieves full 6 DOF motion while standing still and is extremely maneuverable, allowing missions such as ship hull inspections. The lack of a streamlined axis provides equal maneuverability in all axes, but does not allow for efficient cruising. Its small thrusters and battery do not provide enough thrust to reject any but the smallest of currents.

In this paper, we document the design of the Odyssey IV, a hybrid cruising/hovering platform, which gains advantages from both torpedo and cruising vehicle designs. The streamlined axis allows for efficient cruising while the thruster configuration provides hovering maneuverability. All systems have been designed to a depth rating of 6,000 meters, making this vehicle useful for a variety of missions, including deep ocean exploration and sampling and subsea equipment inspection.

Vehicle Design

The Odyssey IV's hull is reminiscent of previous Odyssey class AUVs.[5] It has a teardrop profile, which has proven to be an efficient cruising shape. The vertical axis of the vehicle has been elongated to accommodate the new thruster configuration as well as to improve its passive righting moment. The free-flooding hull is covered by fairings made of ABS plastic. The frame is made of Ultra High Molecular Weight (UHMW) polyethylene, a plastic chosen for its near neutral buoyancy and ease of machining. The inside of the hull remains fairly empty allowing for reconfiguration of equipment as needed. [Figure 1]

The Odyssey IV uses four commercial off the shelf thrusters capable of producing over 200 Newtons of thrust at 1600 RPM. The two cross-body thrusters are mounted in the bow and stern of the vehicle in tunnels that penetrate the hull laterally. The remaining two thrusters are mounted to arms, which protrude out the side of the vehicle and can be rotated about the lateral axis of the vehicle. The thrusters are roughly coplanar with the vehicle's center of mass and drag to minimize rotational couplings with translational movements. Titanium thruster guards protect the vectored thrusters and their arms, which otherwise could easily be damaged on collision. The thruster guards are tied into the vehicle's internal frame to provide extra hard points for vehicle handling. The unit responsible for pointing the vectored thrusters to the desired orientation is the Rotating Thruster Unit (RTU). The RTU consists of a cylindrical housing which contains a brushless motor, a resolver for position feedback and a slip ring which are all coaxially aligned around the shaft that connects to the thruster arms. [Figure 2] The slip ring allows continuous rotation of the thruster shaft without twisting and damaging the cables. The resolver reports angular position measurements within 1/50th of a degree, or 14 bit precision measurements over one rotation. The RTU is oil-filled and pressure compensated.

To provide the power necessary to fight currents and the longevity to dive to full-ocean depth, a custom 4.8 kWh battery that operates at 90-100V was designed.[6] Odyssey IV's battery was based on lithium ion 18650 cells, each with a nominal voltage of 3.7 V and a capacity of 2400 mAh. The battery consists of 24 supercells connected in series, and each supercell is composed of 27 18650 cells in parallel. The cylindrical cells are hexagonally packed into the wedge shaped supercell, and are joined by spot-welding to nickel terminals. The supercells pack roughly in a cylindrical space, which fits in the spherical pressure housing. Each supercell is fitted with custom monitoring boards, which measure voltage, current, and temperature which communicate with a master board. The master board controls the main battery on/off contractor and reports these values to the control sphere via RS232.

Because the RTU, the battery, and the thrusters are extremely negatively buoyant, a large amount of flotation was required. Since the volume enclosed by the hull is limited, the buoyancy per volume of the flotation became an important constraint. Syntactic foam did not perform well on this metric, and is costly to machine. To get maximum flotation for the internal volume, the hull is filled with 300 hollow Alumina spheres produced by Deep Sea Power and Light. These 3.6 inch spheres are depth rated to 11,000 meters and provide 0.6 lbf of buoyancy each.[7] The spheres can be packed into areas where the vehicle shape would make syntactic foam difficult to use, such as between wet cabling. Additionally, if changes are made to the location of housings or instruments the flotation spheres may be relocated easily.

The Odyssey IV is well equipped with a suite of navigation and payload sensors. The vehicle navigates using Doppler Velocity Log (DVL) dead reckoning.[8] Heading control uses a low-cost 3-axis orientation sensor. A pressure sensor for measuring depth and a GPS receiver in a 6,000m rated housing, for verification of vehicle position when on the surface, complete the navigation sensor package. For payload, the vehicle is equipped with a Basler 1.3 megapixel digital color camera. This type of camera, typically used for computer vision, has a high sensitivity CCD sensor, which can deliver images via Firewire at up to 15 fps. For illumination, the vehicle has an efficient, deep-rated and ruggedized 200-joule strobe system. The strobe ballast takes two seconds to fully recharge limiting our effective frame rate to 0.5 fps.

Software

The Odyssey IV runs the Mission Oriented Operating Suite (MOOS), an open source collection of applications and libraries for autonomous vehicle operation, written and maintained by Dr. Paul Newman.[9] In MOOS, the various operations needed to run the vehicle, control, navigation, instrument interface, logging, and user interface are all separate processes. All inter-process communication is done through a central server process called MOOSDB. In addition to the MOOSDB, the Odyssey IV uses the navigation filter supplied by MOOS, called pNav, which takes data from the navigational sensors and, through the use of an Extended Kalman Filter (EKF), is able to calculate its location.

Several new applications have been written to extend the capabilities of MOOS to accommodate the Odyssey IV's unique capabilities. pHelmSG is a two-tiered, behavior-based control process. [Figure 3] In the top tier, missions, which are collections of behaviors that are run in series or in parallel, take nav-filtered sensor data and generate position errors, velocity errors, or open-loop force requests. Behaviors can also send commands to the rest of MOOS which have nothing to do with actuation, for example telling the camera/strobe system to take pictures at a specified frame rate. Multiple missions can be read on startup and stored internally, allowing the operator to switch between them easily.

Once the active behaviors have made their body axis requests, they get passed to the lower tier of pHelmSG. The requests are prioritized and, if there are conflicting requests for a given axis, only the highest priority request is accepted for that axis. If the request is closed-loop position or velocity, it is passed through a PID controller, which will output a desired force for that axis. These forces are then passed to the low level controller, which maps body axis forces to actuation commands.

The low level controller takes the forces that were calculated by the PIDs or directly from the behaviors and maps them into actuation commands. For the Odyssey IV, the valid axes of control are surge, sway, heave, and yaw. Surge and heave are governed by the vectored thrusters, surge being pure forward and heave being purely vertical. The desired force vector of these side thrusters then is simply the superposition of these two component force vectors. The RTU angle is set to the direction of the force, and the resulting force requested on the vectored thrusters is the magnitude of the vector sum. Yaw force is achieved by differentially driving the cross body tunnel thrusters and sway is achieved by driving them together. These cross-body force requests are simply added to one another. Once the force requests have been calculated for each thruster, they are converted into RPMs using the relation that force is proportional to propeller RPM^2.

A new logging system was developed to quicken user access to data when the vehicle is on the surface. Using the logger supplied with MOOS, all mission data are stored in multi-column ASCII text files. Though this has the advantage of allowing the logs to be both human and machine readable, it means that the entire file must be transferred before visualization can be rendered on the operator's computer. As these files can be relatively large, on the order of tens of megabytes, and wireless communication can be slow, these transfers can take several minutes. For a one-time transfer this delay is not excessive for a patient operator, but for frequent and repetitive missions where data must be inspected between missions, this can lead to more vehicle idle time than is desired.

By using a database server as the storage mechanism for all the vehicle's data, the operator can query only the variables of interest, and pipe the data directly to a plotting or other visualization program. This eliminates the communications bottleneck and shifts the burden to the onboard computer, which must sort through the data to retrieve only that which has been requested. The particular database implementation used on the Odyssey IV is MySQL, an open-source, efficient and scalable DBMS. The server/client architecture of MySQL works well for querying between hosts as is necessary between the operator's laptop and the vehicle. Given the increased processing power of embedded systems in recent years, the efficiency of MySQL, and the relatively low processor requirements of MOOS, the queries are typically processed very quickly. A client application, MOOSPlot, was developed to allow the user to browse the data and to graphically select which variables are to be visualized. They are then retrieved and plotted, typically in a few seconds or less.

A graphical control panel was developed to facilitate ease of operation and to minimize surface time of the vehicle. It was developed in Python using the wxWindows cross-platform GUI library for portability and ease of development and modification.[10] The interface allows the operator to browse missions currently loaded in pHelmSG by name. When a mission has been selected, the user may generate a preview graph of the mission by pressing a button. This preview, generated by GraphViz, an open-source text based graph generation program,[11] allows the user to visualize the conditions under which various behaviors are triggered. [Figure 4] This can be an invaluable tool for proofreading a mission for typographical errors.

In order to have a Python application, such as this graphical control panel, connect to the MOOS community on the vehicle, python bindings were created using the Simplified Wrapper and Interface Generator (SWIG). SWIG allows libraries written in C or C++, like MOOS, to be linked with Python libraries.[12] The result is that the inter-process communication data structures and routines of MOOS are now available within Python.

Trials and Field Operations

In the late winter and early spring of 2007, the Odyssey IV first touched the water for a series of pool tests at the University of New Hampshire’s Ocean Engineering Lab. With the vehicle in a safe, controlled environment, we were able to test each of its subsystems. While most worked as expected, a few unforeseen flaws were detected. As a result of an unstable righting moment, the battery required relocation to the lowest point possible to move the center of mass further below the center of buoyancy. Also, the motor controllers for the thrusters were observed to heat up to 80 degrees Celsius, near their maximum rated operating temperature when the thrusters were under moderate load. An active liquid cooling system was developed soon thereafter to pump the heat out to a heat exchanger external to the control sphere, where it could be dissipated into the surrounding water. The vehicle's hovering ability, closed-loop position control of all four axes, was tuned to allow it to maintain its desired position with centimeter scale precision. [Figure 5] Pitch instability was observed when the vehicle moved at high velocities in surge, so pitch-stabilizing fins were added at the stern of the vehicle.

In June 2008, the Odyssey IV was first deployed in open water for a series of field tests off of Falmouth MA aboard the "R&R," a research vessel owned and operated by Ryan Marine Services, Inc. During these tests, we tuned the cruising capabilities of the Odyssey IV. [Figure 6] The vehicle body appeared to be unstable in yaw when cruising forward approximately 1 m/s. Large yaw fins were added to the tail of the vehicle to correct for this instability. Further investigation indicated that the instability was due to the use of the cross-body thrusters for yaw control when cruising. The yaw force generated by the cross-body thrusters tends to lag the commanded force due to the volume of water in the cross-body tunnels.[13] Additionally, there is a loss of thruster efficiency due to hydrodynamic hull-attachment effects on the body during cruising.[14] Despite these difficulties the Odyssey IV's navigation filter and control PIDs were tuned to demonstrate successful survey patterns for upcoming missions.

In July 2008, the Odyssey IV was deployed from the NOAA ship Henry B. Bigelow in Georges Bank. [Figure 7] Its mission was to map the percent coverage of *Didemnum*, an invasive tunicate known to infest Georges Bank and of great concern to the local fisheries.[15] In two days of successful operation, the vehicle covered 39.3 km of rocky bottom, taking 1.3 megapixel images and high frequency Didson sonar data. [Figure 8] During this deployment, the Odyssey IV was stress tested through repeated survey missions. As a result of these stress tests, a weakness was found which lead to erratic control behavior. The RTU was observed to bind in a constant orientation when the vectored thrusters were producing large forces, resulting in a lack of control over the surge and sway axes.

Further testing of this failure mode led to the understanding that the three-piece thruster shaft may have deformed under load and required replacement with a solid one-piece shaft. Additionally, the RTU motor mounting bracket, when heated by the motor under constant use, softens the PVC bracket enough to allow the screws holding it in place to loosen. When these screws are loose, the motor is allowed to rotate within the housing independently of the resolver. This angle differential is great enough to incite a failure mode in the motor controller and stall the RTU motor. To resolve these issues, the thruster shaft was welded together and the RTU motor mounting bracket screws were reinstalled with thread lock, spring lock-washers, and the maximum allowable torque. The PID gains controlling the RTU rotation were also turned down to decrease the rotational force on the motor mount. In the spring of 2009, the RTU failure analysis and repairs were completed and tested in the lab. The RTU was operated for several hours at the maximum allowable rate with the thrusters loaded with the appropriate force with no observable failures.

Conclusion and Future Work

The Odyssey IV has shown to be a promising platform for subsea observation. It has demonstrated the ability to perform survey missions as well as an Odyssey II class vehicle, which was designed for such a purpose. The vehicle has also shown that it can precisely hold its position to within centimeters of its desired location.

One of the shortfalls of the Odyssey IV's control that needs to be addressed is heading control in a cruising scenario. Using the cross-body thrusters does not provide a quick enough response to adequately reject intrinsic vehicle instabilities. It has been noted that while the vehicle is cruising, much more surge force is requested than heave force. The effect of this is that the vectored thrusters are nearly horizontally oriented. Thus, they can be differentially driven to create a yaw force without inducing a large roll moment. Using the vectored thrusters to control heading would be highly advantageous in a cruising scenario for several reasons. They are separated from the vehicle body so as to eliminate the loss of efficiency due to hydrodynamic hull attachment effects. They also do not need to move the large volume of water as the cross-body thrusters, which are in long tunnels. Finally, they will be spinning at relatively high RPMs already due to the surge forces they will be creating, and therefore will not have to deal with thruster dead band as they repeatedly reverse direction.

The addition of an acoustic modem will allow for communication with the vehicle while it is submerged. Of particular interest will be the ability to send high-level commands to change the vehicle's behavior. In a supervisory control scenario, the operator can be more interactive with the vehicle than is typical of AUVs. New set points for X/Y position, heading, depth or altitude can be transmitted to the vehicle while it is performing closed-loop control over these axes. With the vehicle handling the control loop, the bandwidth requirements for these commands are trivial. This type of control is particularly useful for hovering vehicles such as the Odyssey IV.

We are also planning to completely re-task the vehicle while it is underwater. Since pHelmSG loads many missions on startup to be selected by name, only a small mission identifying string would need to be transmitted in order to change the mission. Additionally, missions could be rerun with slight parameter changes. An example of this would be to systematically survey large areas of bottom by performing a smaller survey, returning to a known location for transmission, relaying necessary information, and then maintaining position while awaiting further input. In this way, the operator could retask the vehicle, but save a costly round trip to the surface and back. A further extension of this would be to transmit entire missions to the vehicle. Since a mission configuration file is simply a small ASCII text file, it could be transmitted in its entirety over the acoustic link. For all of these command scenarios strict acknowledgment and verification procedures would need to be put in place, so the vehicle would not act upon corrupted information.

As previously noted, the vehicle is equipped with a computer vision capable camera. The addition of continuous lighting would allow for visual servoing and navigation. Given the unique actuation style of this vehicle, it would be possible to perform visual-based pipe following missions both vertically and horizontally. Similarly, docking using visual feedback and high precision control could be performed from the top, bottom, or front of the vehicle. Mosaic based navigation,[16] as a way of decreasing navigational errors is another area of interest.

While the decreased RTU position PID gains are an acceptable method of preventing damage to the RTU, a redesign of the RTU motor mount would allow the RTU to rotate at the maximum allowable rate and therefore decrease any lag in the vehicles vectored thruster response. This decrease in lag would allow for more agile position corrections, and could potentially allow the vehicle to traverse closer to obstacles than is currently acceptable. It would also allow for the PID to operate much closer to the ideal control model with minimum position overshoot. Eliminating the overshoot with the current motor mount would almost certainly result in RTU failure, but would allow the vehicle to be more precisely controlled in close quarters to obstacles.

Acknowledgments

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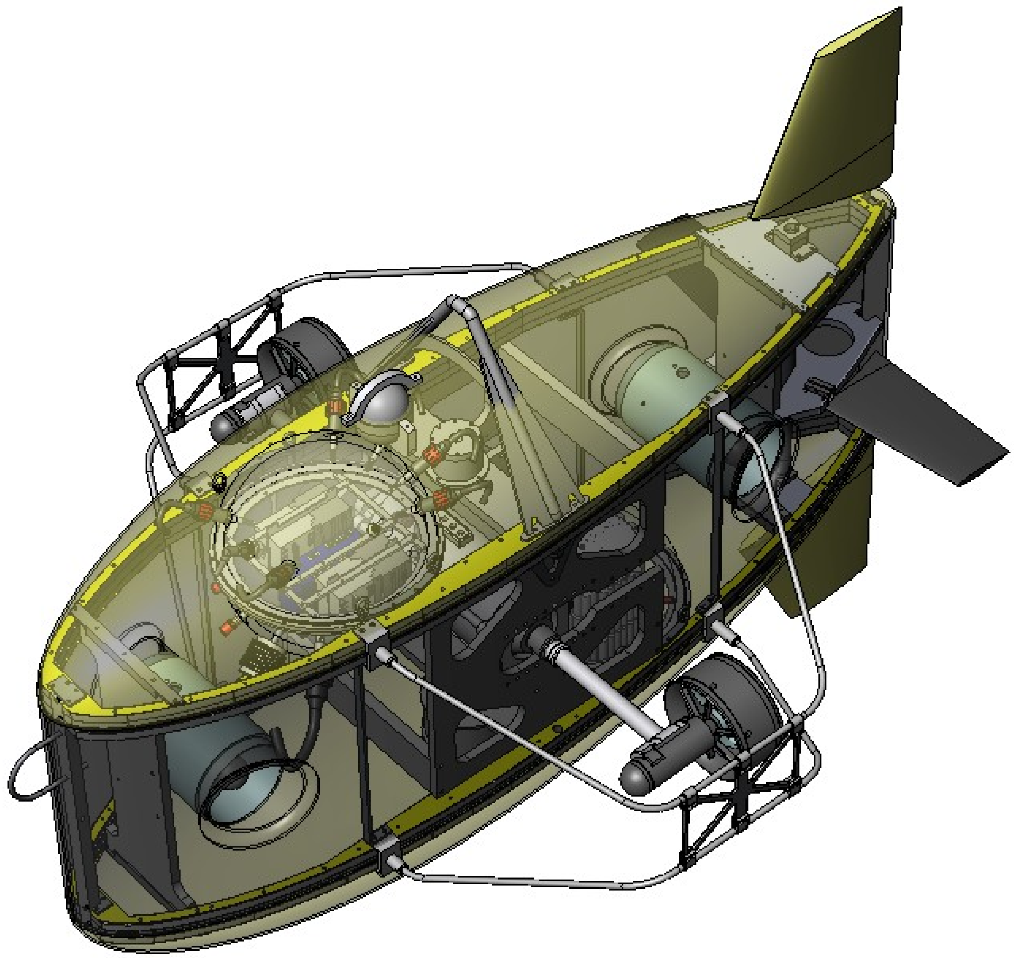

Figure 1 – Solidworks drawing of Odyssey IV exhibiting the current vehicle configuration.

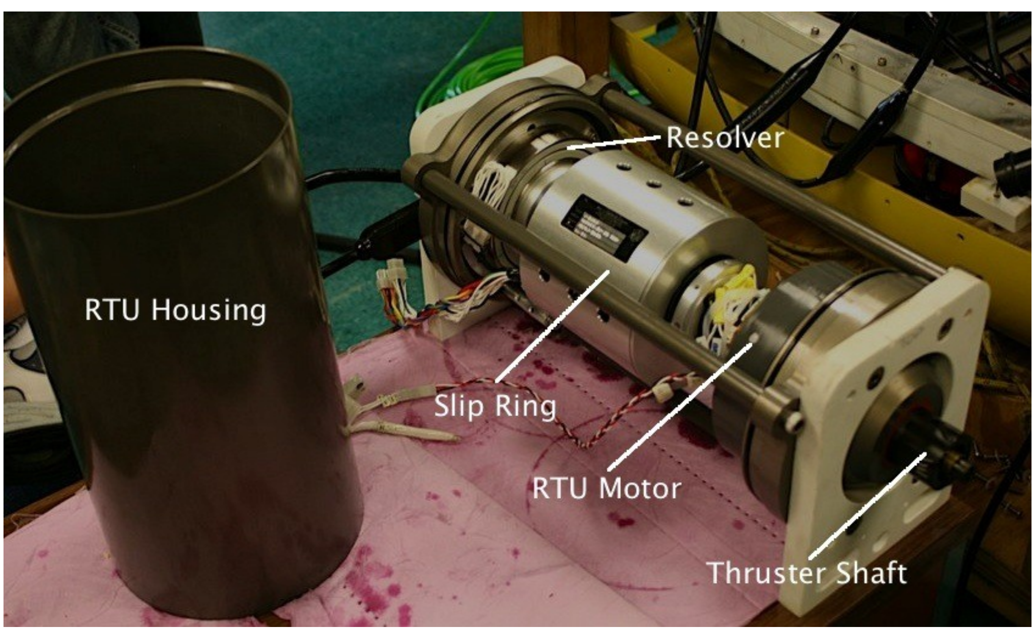

Figure 2 – RTU Removed from housing, assembled and working in this image.

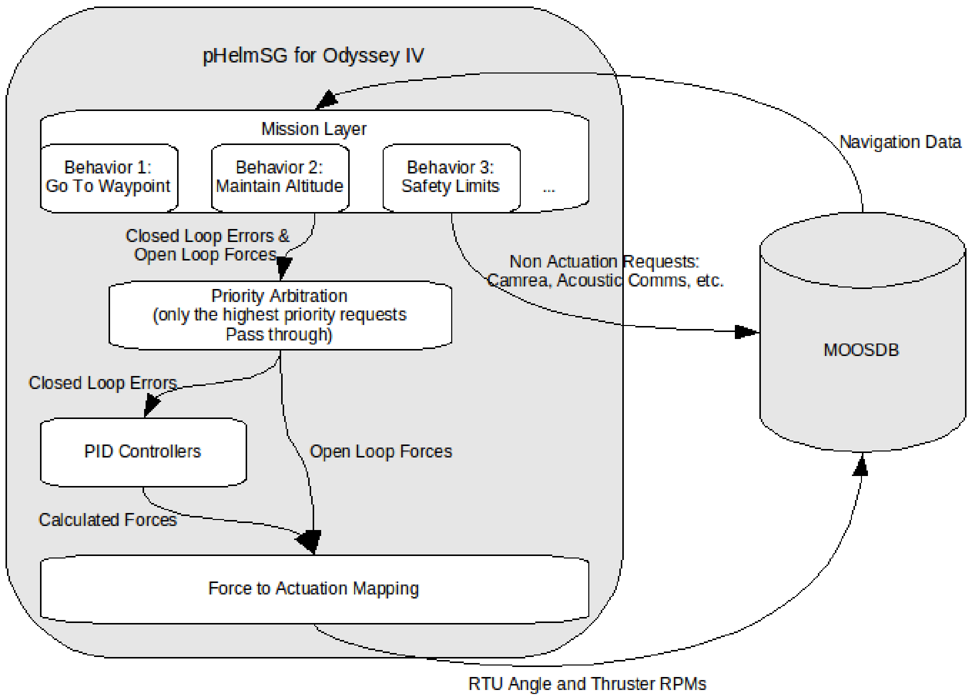

Figure 3 – Data path within pHelmSG. All communication with other processes goes through MOOSDB, the MOOS inter-process communication server.

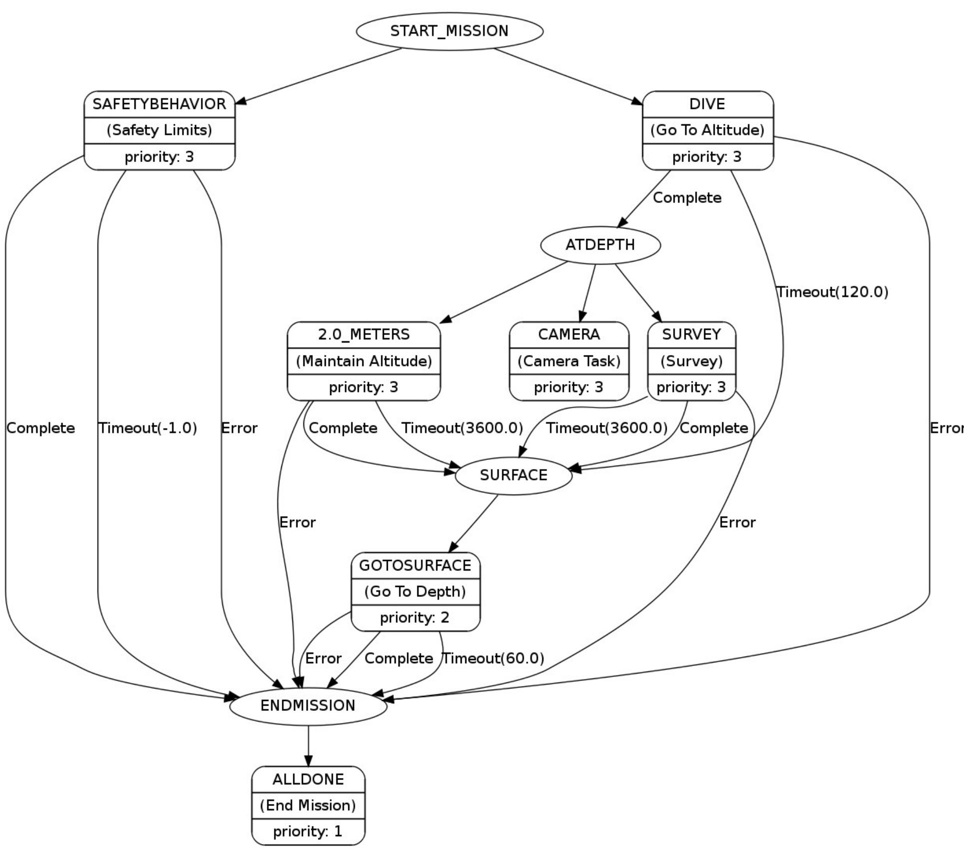

Figure 4 – Sample mission preview as generated using GraphViz. This shows a typical survey mission.

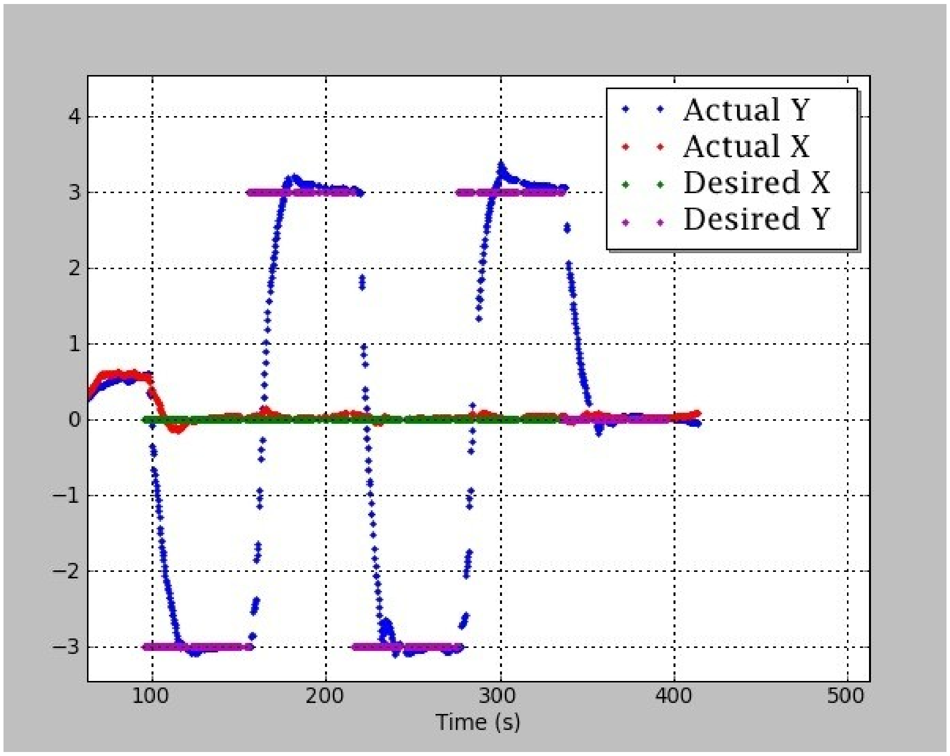

Figure 5 – Plot of actual X and Y coordinates in red and blue respectively compared to desired X and Y coordinates in green and purple. These tests were conducted in a controlled environment. This graph demonstrates centimeter level precision when hovering.

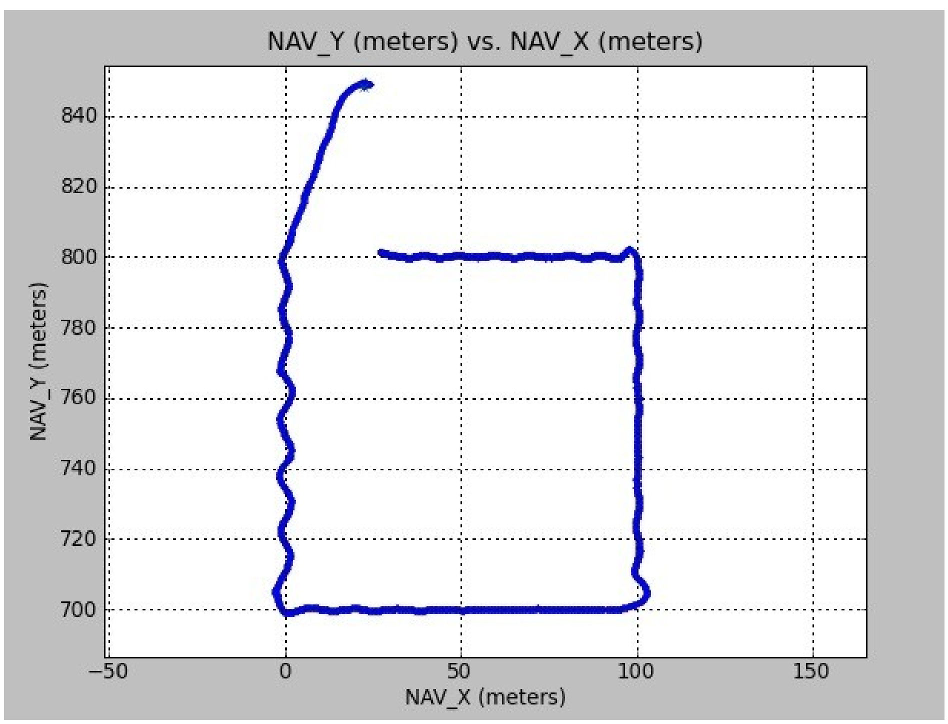

Figure 6 – Graph of actual X and Y vehicle path attempting to navigate through the four corners of the square in succession. Note that heading control is acceptable for survey work, but shows the known issues of heading control using cross-body tunnel thrusters when cruising.

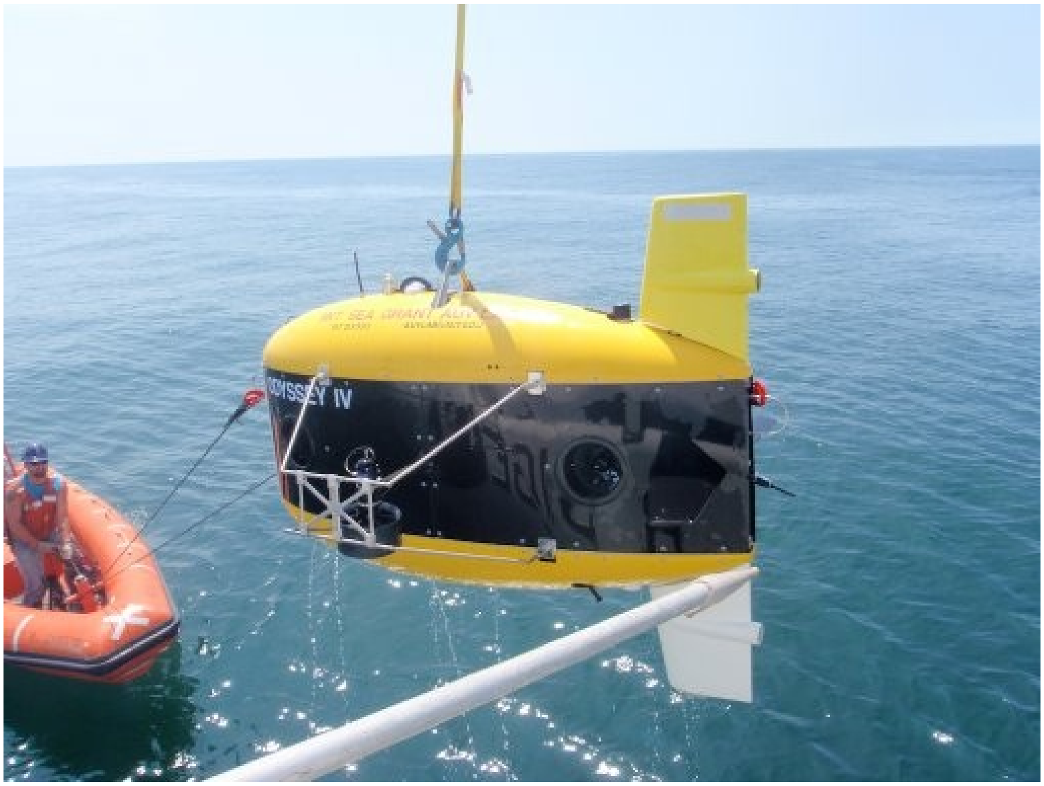

Figure 7 – Odyssey IV recovery from the NOAA vessel Henry B. Bigelow.

Figure 8 – Photograph taken at 50 meters from the Odyssey IV camera of Didemnum at Georges Bank.