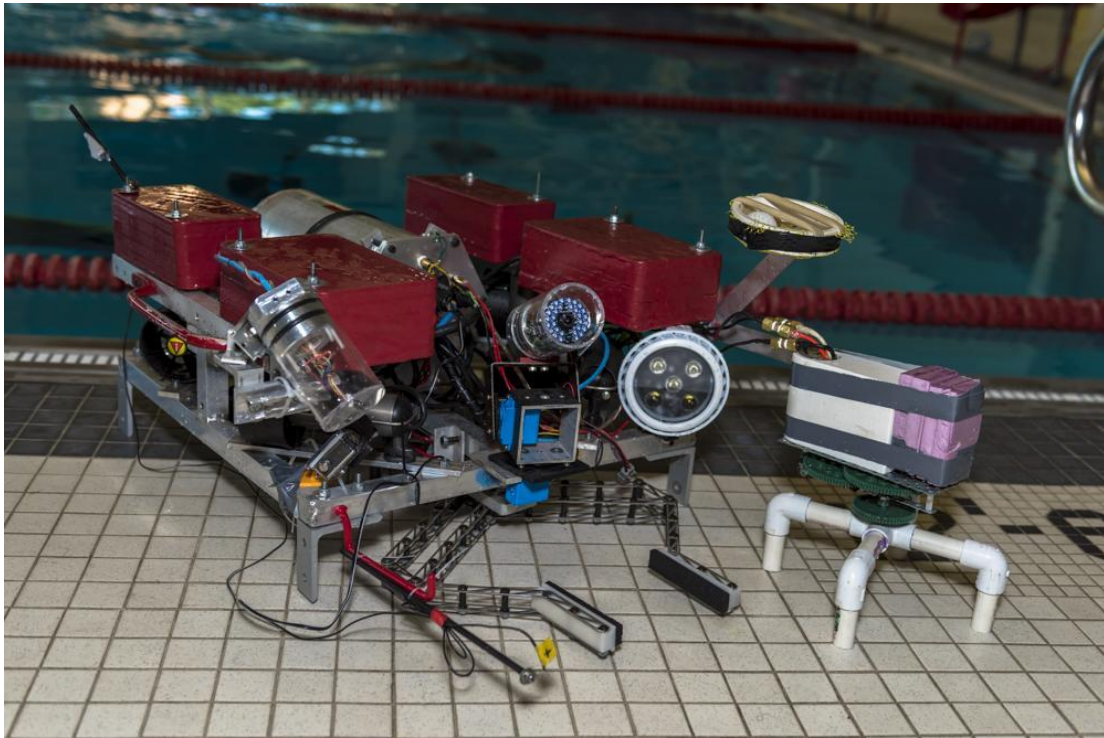


AEGIR

Rose-Hulman Robotics Team

Rose-Hulman Institute of Technology, Terre Haute IN, USA



2015 MATE ROV Competition

June 24th 2015

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Abstract

The Rose Hulman Robotics team (RHRT) is a student-led company based at the Rose-Hulman Institute of Technology in Terre Haute, Indiana and a four-year participant in the Marine Advanced Technical Education (MATE) underwater robotics program. RHRT's newest remotely-operated vehicle (ROV) is named *Aegir*, after a legendary Norse giant associated with oceanic festivity. *Aegir* is a work-class ROV designed to be equally at home conducting subsea research missions or maintaining underwater infrastructure, with a focus on Arctic marine environments. Potential tasks include iceberg survey, specimen collection, pipeline repair, wellhead operations, and visual inspection.

While many lessons and ideas from previous ROVs have been incorporated into *Aegir*'s design, it is a completely new vehicle, representing a fundamental overhaul of RHRT's approach to project organization and product design. In its basic configuration *Aegir* measures 52cm wide, 75cm long, and 35cm tall to facilitate deployment through small openings such as holes in ice sheets. Its primary camera is equipped with a 2-axis servo gimbal to allow the pilot to easily view the underwater environment without moving the ROV. All communication between the *Aegir* and the surface is through a single Ethernet cord. Both pneumatic and electrical power are available to supply mission tools, allowing for flexible deployment of a wide variety of manipulators depending on the requirements of the mission.

The bulk of design and fabrication took place between September and December 2014, with testing, refinement, and development continuing through May 2015. The total project budget was approximately \$18,800, provided primarily by Rockwell-Collins.

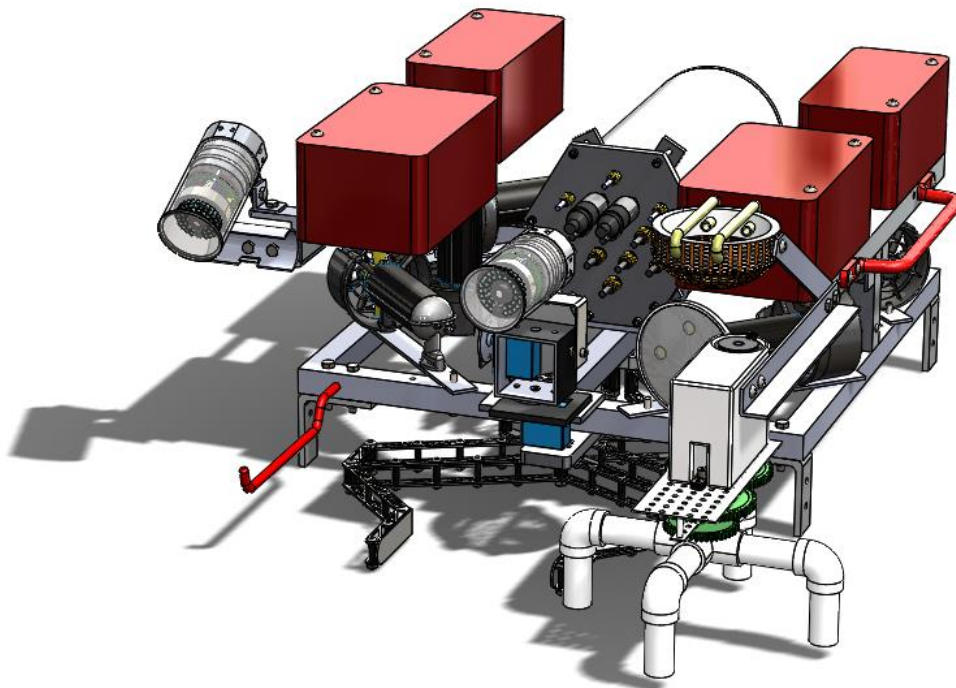


Figure 1: *Aegir* modeled in SolidWorks 3D drafting software.

Table of Contents

Abstract	1
Table of Contents	2
Safety	3
Design Narrative	4
<i>Prior Art</i>	4
<i>Project Planning</i>	4
<i>Component Selection</i>	5
<i>Thrusters</i>	5
<i>Control System</i>	6
<i>Sensors and Vision</i>	6
<i>Pressure Vessels</i>	6
<i>Frame</i>	7
<i>Core Vehicle Construction</i>	7
<i>Manipulator Design</i>	7
System Interconnection Diagram	9
Subsystem Overview	10
<i>Primary Electronics Canister</i>	10
<i>Frame</i>	11
<i>Buoyancy and Ballast</i>	11
<i>Waterproof Connections</i>	12
<i>Propulsion</i>	13
<i>Software</i>	14
<i>Power Distribution</i>	15
<i>Control System</i>	16
<i>Vision System</i>	17
<i>Pneumatics</i>	18
<i>Parallel-Jaw Gripper</i>	18
<i>Inertial Measurement Unit</i>	19
<i>Valve Turner</i>	19
<i>Pipe Clamp</i>	29
<i>Algae Collector</i>	20
<i>Additional Tools</i>	21
Project Costing	22
Retrospective	23
Future Plans	24
References	25
Acknowledgements	25

Safety

Safety is RHRT's number one concern. The team firmly believes that safety needs to be proactive instead of reactive and diligently adheres to a set of procedures and precautions to make sure that its members are always safe.

Team Member Safety

Only qualified team members are allowed to enter the workspace. To be considered a qualified team member, students must take a business safety exam and become familiar with the hazards and safety concerns in the workspace. Qualified personnel entering the workspace are always required to wear safety glasses, long pants, closed-toed shoes. Other personal protection equipment (PPE) such as welding masks, gloves, and hearing protection is issued as appropriate.

ROV Safety

All vehicle power runs through a 30A quick-blow breaker, which cuts power in case of an electrical fault. Electrical systems on the surface and underwater are fully insulated to prevent any possibility of an electrical shock. Care was taken to remove sharp edges and corners from the ROV frame. Although pressurized air is used to provide power for some mission tools, the system is only pressurized when it is actively being used and is always depressurized when being transported or maintained. The six electric thrusters are fully shrouded and are positioned within the outer extent of the frame.

During pool tests the team adheres to the following **SAFELEE** procedure:

Survey location. Make sure that the table for the control computer is at least six feet from the water. Ensure that bystanders are clear from the area of the pool used for the mission. Survey the deck to make sure it is clear of obstacles and tripping hazards.

Address any issues observed. Remove hazards from the deck, move to a new lane if necessary.

Fixture the mission items. Deploy divers to set up mission targets depending on the task. Divers are always aware of the position of the ROV and keep well clear while it is powered.

Evaluate readiness. Make sure that all crew members are attentive, clear of any moving or powered systems, and ready for the mission to begin. Check that ROV-computer connection is successful and that all electrical systems are running normally.

Launch the ROV. At least two members deploy the ROV into the water from the deck, as the mission begins.

Exit the area. Remove all of the mission props from the water and all team equipment from the pool side prior to leaving the area. ROV is rinsed in fresh water to prevent corrosion before returning to the work area.

Examine the results. Perform a post-mission inspection to make sure all the seals were maintained. The results of the test run are discussed with appropriate attention given to safety issues and areas for future improvement.

Workspace Safety

Robotics work is conducted in the university's Branam Innovation Center (BIC), which includes work bays, a machine shop, and welding equipment for use by project teams. Access to the BIC is tightly controlled and all team members must take a safety exam before they can enter the workspace. Areas with equipment requiring a high level of training to use safely, such as the machine shop, require further access permissions, and members are subject to additional training before they can enter these areas. Use of the buddy system is mandatory when working in the machine shop. In addition, the workspace is monitored by trained staff who can offer technical or emergency assistance.

Design Narrative

Prior Art

No engineering project exists in a vacuum, and the cutting edge of modern technical development is built on the shoulders of decades of previous work. Many important decisions in *Aegir's* design process directly resulted from experience in previous years' efforts and observation of successful designs from other teams.

While *Aegir's* predecessor, *Skippy Mk II*, was more successful than previous RHRT ROVs, the project was plagued by design and management issues that ultimately prevented the team from moving past the regional level. *Skippy's* pressure vessel and electrical connectors frequently leaked, flooding the electronics enclosure and disrupting vehicle communication. Although *Skippy* was equipped with three exceptionally powerful Videoray thrusters, its structure was not designed with much consideration for hydrodynamics, making it very difficult to precisely control.

Additionally, the team's schedule was not planned to allow for testing and refinement. Manufacturing delays pushed back completion of the vehicle until mid-April, which resulted in the presence of several major software, electrical, and mechanical issues during the regional qualifier.

RHRT's greatest challenge for 2014-2015 was identifying an approach to ROV design that would result in a successful final product. The team's efforts during *Aegir's* design process were essentially a large-scale stepping back from the organizational patterns that had previously proved unsuccessful, as well as a commitment from all members to apply good engineering practice and project management techniques to produce a successful and technically-impressive final product.

Project Planning

At the start of the academic year in September, with an eye towards the experiences of the previous year, the team set the following overarching goals to guide the ROV design process through the end of May:

1. **The ROV must be capable of operating underwater early in the build schedule to permit testing and refinement.** Many teams leave the fabrication and testing of their ROVs until the last few months before the deadline. RHRT decided to reject this practice, and worked to finish the ROV as soon as possible to give plenty of time to troubleshoot and make improvements.
2. **The ROV must be consistently controllable and highly maneuverable with 4 or more degrees of freedom.** Flexibility and precise movement are critical to accurate completion of mission tasks. Maintaining neutral buoyancy and eliminating asymmetric fluid drag are vital to ensuring the ROV remains level under all operating conditions.
3. **The ROV must be exceptionally watertight.** Even a slow leak through connectors or bulkhead joints could have a crippling effect on vehicle testing and performance. Robust waterproofing methods are a worthwhile investment, since money spent on reliable connectors will be saved in troubleshooting faulty systems and replacing water-damaged components.

In order to meet the goal of producing a minimally-viable ROV as quickly as possible, a schedule, shown in Table 1, was assembled that would have the ROV functioning underwater by the end of November. Additionally, the team decided to begin vehicle design and fabrication before the specific requirements of the mission were known. While this presented a challenge in that the ROV design would have to accommodate any possible mission, analysis of past missions revealed that many featured similar tasks and required the ROV to accommodate a relatively narrow range of requirements. The team theorized that it would be possible to build a ROV that could accomplish any conceivable mission. The initial mission briefing was released during this design stage. It provided general guidelines such as a maximum ROV dimension of 75cm x 75cm, as well as the need for sufficient power to overcome the current in the flume tank. The overall project goals and the mission restrictions provided an initial set of design guidelines that allowed more detailed ROV design to begin.

Table 1: Gantt chart for vehicle design and construction process.

	9/7	9/14	9/21	9/28	10/5	10/12	10/19	10/26	11/2	11/9	11/16	11/23	11/30
Pressure Vessel	█	█	█	█	█	█	█	█					
Prototype Control System	█	█	█	█	█	█							
Frame			█	█	█	█	█						
Control Software			█	█	█	█	█						
Vision Software			█	█	█	█	█	█					
Tether							█	█					
Control System Integration						█	█	█	█				
ROV Integration									█	█	█		
Operational Testing											█	█	█

Component Selection

The team identified a general order in which design choices should be made regarding components to prevent conflicts, shown in Figure 2 below:

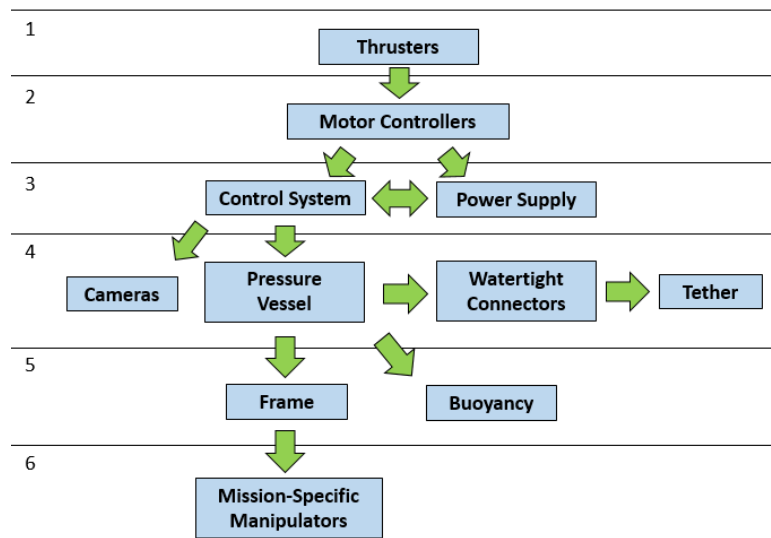


Figure 2: Design priority flowchart.

Thrusters

The number and type of thrusters was an important starting point since it dictated the parameters of the control system, which in turn determined the size and shape of the main watertight canister as well as the overall shape and frame of the ROV. Team discussion of thrusters brought up a variety of options, including custom thrusters and Videoray brushless thrusters. A tradeoff analysis showed that designing custom thrusters would consume a very high amount of effort without the guarantee of a functional product. Previous experience with Videoray thrusters indicated that they required mounting on a flat watertight bulkhead to work reliably. The team ultimately decided to purchase new SeaBotix thrusters because they were completely independently watertight and would provide sufficient thrust to move the ROV without overdrawing the power supply system. A 6-thruster system was devised to provide precise vectored thrust and to take maximum advantage of the operator's three-axis joystick.

Control System

The onboard control system was designed around the Beaglebone Black single-board computer, selected for its powerful processor and built-in Ethernet and USB. This was the core of the control system on *Skippy MkII*, so the team decided that it would be in its best interest to use a familiar system rather than start from scratch. The remaining elements of the control system were selected based on the requirements of the thrusters, the available input and output types on the Beaglebone Black, and the expected requirements of the mission-specific tools.

Sensors and Vision

Vision systems on previous ROV projects had included USB webcams and composite-video camera boards. While these systems provide useable video, they had several drawbacks which made them undesirable. The composite video signal required a shielded coaxial cable to prevent interference in the tether, which made the tether very bulky if multiple cameras were used. The USB webcams were found to overload the Beaglebone Black's single USB host, making it difficult to view multiple camera feeds in real time. Routing the video feeds over a common Ethernet network would alleviate these problems, since Ethernet is tolerant of interference and capable of handling high-bandwidth signals. Ethernet security cameras were therefore selected to provide the ROV's primary sensor capability.

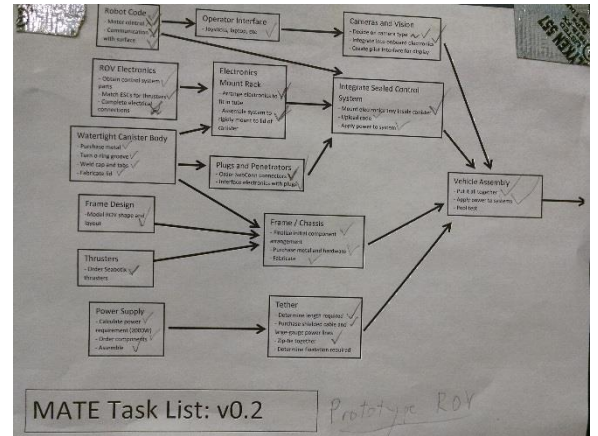


Figure 3: Design flowchart created to manage initial prototyping tasks.

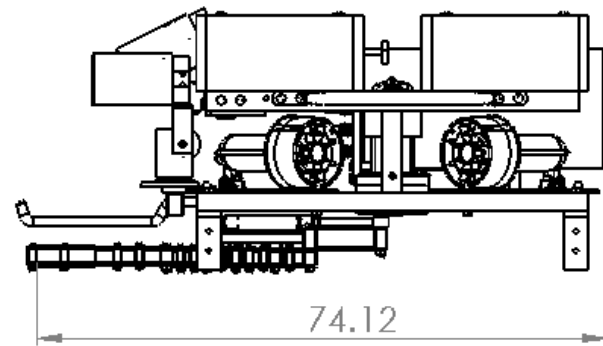
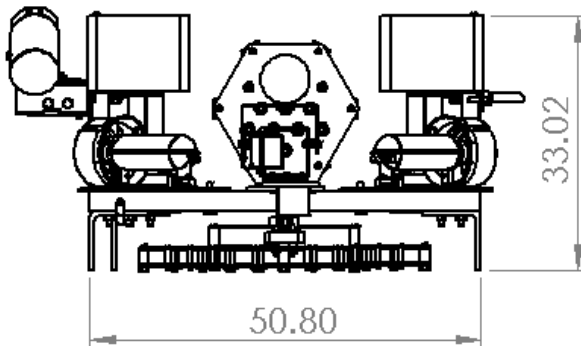
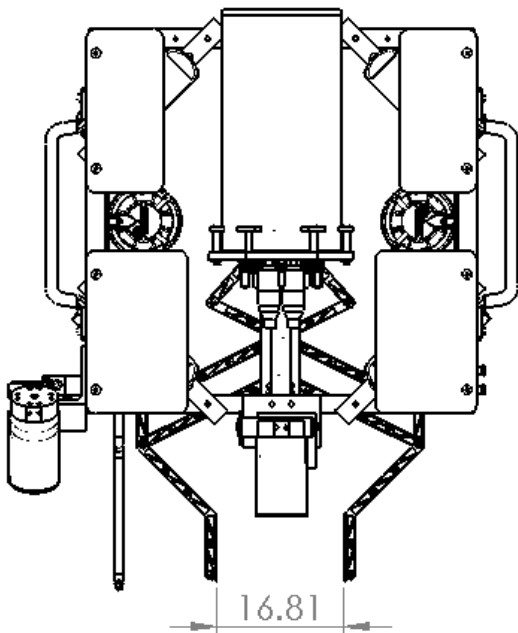


Figure 4: Three-view drawing of core *Aegir* ROV. Dimensions in cm.

Pressure Vessels

Development of prototype pressure vessels had begun during the summer of 2014 in response to unsatisfactory performance of *Skippy's* pressure vessel. Two finalized designs had emerged by the start of the design process: an aluminum cylinder with a sealing mechanism based on planar compression of an O-ring, and an acrylic tube that sealed through a radially-compressed O-ring and an aluminum plug. While both were much easier to open and maintain than *Skippy's* vessel, the cylinder design was determined to be sturdier and more easily scalable, so it was chosen as the basis for the electronics canister. The acrylic design was transparent and easier to fabricate, so it became the basis for the camera containers.

Frame

Once the important constituent parts were specified, a frame was designed to support them. Important factors in the design of the frame were the ability to make modifications and the availability of locations near the perimeter of the ROV for mounting mission tools. A square frame made of square aluminum tube was ultimately chosen due to its simplicity, durability, and the ease of adding additional holes as required. The frame was TIG welded to insure joint strength and to take advantage of existing team experience.

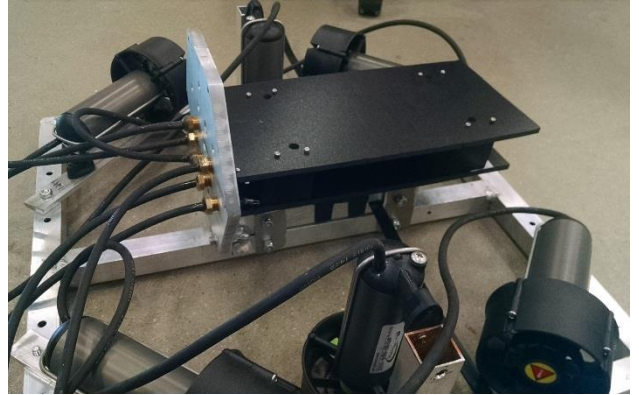


Figure 5: *Aegir* frame during thruster integration.

Core Vehicle Construction

Fabrication of ROV components began in early October, once the core design specifications were available. All parts of the ROV were manufactured by student team members. Manufacturing took place in the Robotics Team's work bay in the Branam Innovation Center, in the Department of Mechanical Engineering's machine shop, and at the Rose-Hulman Ventures facility. Work proceeded in parallel on the electronics canister and the frame, with coordination between the design teams to make sure that the parts would be mechanically compatible when completed. A virtual assembly was created in SolidWorks computer-aided design (CAD) software to generate manufacturing drawings and prevent component interference.

A prototype version of the control system was functional by mid-October, in time to be interfaced with the newly-arrived SeaBotix thrusters and SubConn electrical connections. Bench testing was conducted to evaluate the functionality of the pilot interface and the vectored thrust algorithm. Work proceeded on integrating the cameras with the communication system and receiving the video feed on the surface.

The pressure vessel was completed and successfully tested in the pool at the beginning of November. Fabrication of the camera housings and the transfer of the camera boards from their original enclosures occurred at this time as well.

Integration of electrical systems into the pressure canister and mounting of the completed canister onto the frame occurred in mid-November, resulting in a functional and watertight ROV system. The first powered pool test took place in early December. All pressure vessels remained watertight, although the ROV buoyancy and ballast required adjustment to keep the vehicle level while minimizing total mass and displacement.

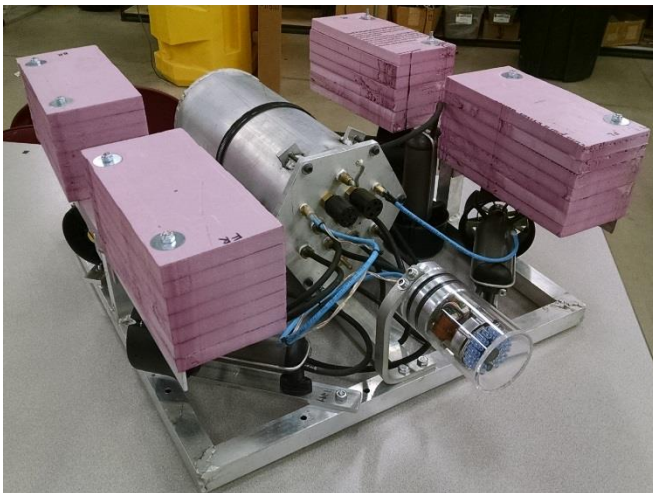


Figure 6: *Aegir* following final system integration.

Manipulator Design and Testing

December was occupied by initial ROV testing and troubleshooting, coinciding with the release of the full mission manual. A simple servo-based gripper was fitted to allow *Aegir* to interface with items underwater, but it was too weak to grip the heavier items expected in an actual mission. In response the team developed a pneumatic gripper, which proved suitable for a wide variety of mission tasks. This gripper was chosen as the basis for the final primary manipulator system.

The focus of early testing was on completing the tasks that would be present at the regional qualifier event; the team highly valued a successful qualifying run, which would insure its participation at the international event. Therefore the mission tools associated with the wellhead and hot stab tasks took immediate precedence.

Analysis of the mission tasks was conducted to determine the order in which they should be attempted and to approximate how much time should be devoted to each. This analysis led to the decision to build a dedicated mount for the hot stab, which would allow the primary gripper to be used during the wellhead sequence while eliminating an additional trip to the surface to exchange equipment. While testing showed that the ROV could use its grabber to open or close a valve, the large number of valves involved in the pipe flow task convinced the team to develop a dedicated valve turning attachment to turn all six valves as quickly as possible.

Other manipulators were developed as required and revised as testing exposed oversights and weaknesses. The underwater electrical testing system originally used an LED to indicate potential between its magnetic contacts, which worked successfully on the surface, but testing in the pool showed that the chlorinated pool water would effectively short the contacts and pull the potential below any LED's minimum threshold. This forced the team to develop an alternate solution using the Beaglebone Black's analog input port to measure the very small electrical potential.

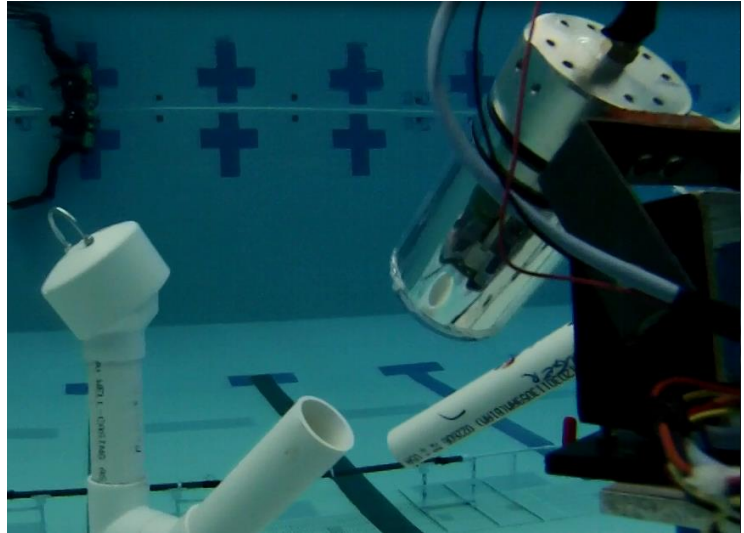


Figure 7: Still frame from onboard GoPro camera recording of qualifying mission attempt at Shedd Midwest regional.



Figure 8: RHRT competition travel crew in late May with *Aegir*. Clockwise from upper left: Nathan Blank, Joe Schornak, Cody Bressler, Sam Lawrence, Colton Watson, Betsy Tainer, Peter Heath.

ROV Systems

Surface Station

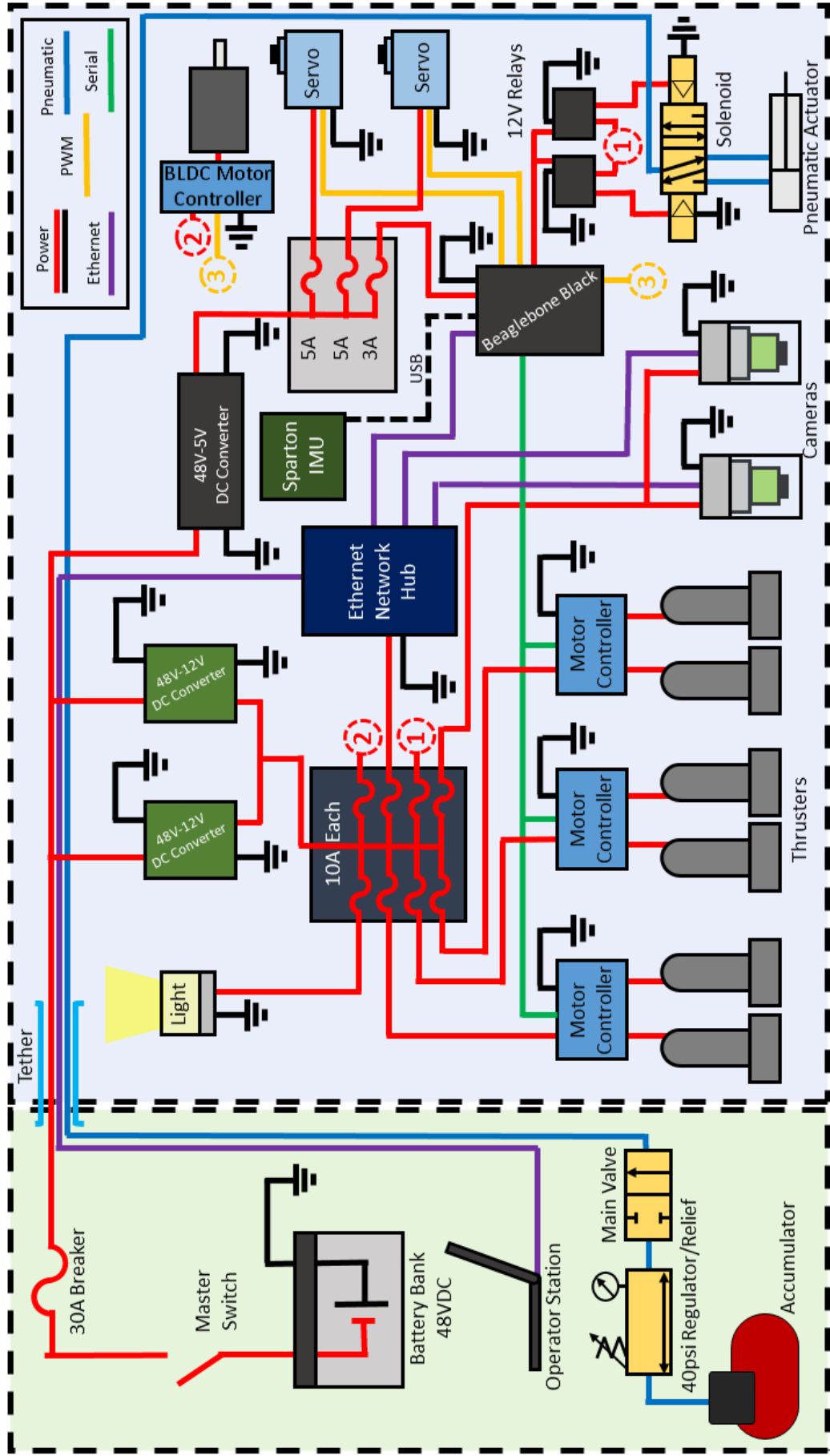
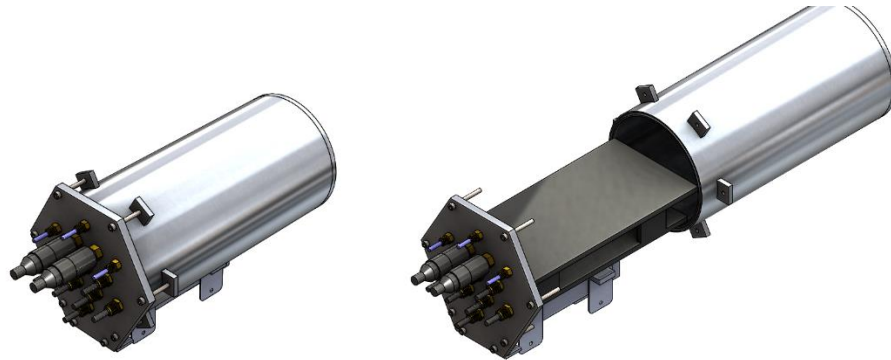


Figure 9: Aegir system interconnection diagram

Subsystem Overview

Primary Electronics Canister

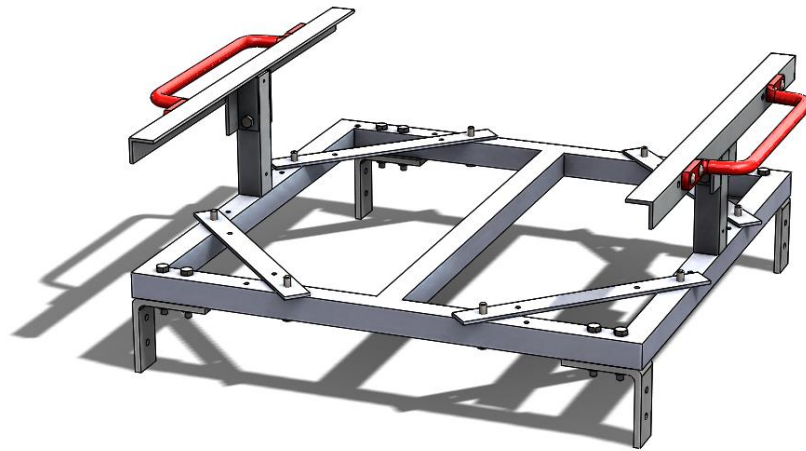


Purpose	Components and Features
<p>Central enclosure for the main computer, motor controllers, power converters, communication hub, and pneumatic solenoid. Protects delicate electronics from water damage.</p>	<ul style="list-style-type: none"> ● Body: 15.24cm-diameter 0.635cm-thick 6061 aluminum cylinder with welded 0.635cm 6061 aluminum cap ● Lid: waterjet-cut hexagonal 0.9525cm-thick 6061 aluminum plate. ● Sealed by 0.3175cm-thick 14.92cm-diameter Buna-N O-ring compressed by 6 screws between lid and body. ● Double-decker cantilevered plastic electronics rack fixed to lid ● Lid and electronics rack remain integral to ROV when canister is removed, facilitating maintenance.

Overview: The success of the electronics canister design is absolutely critical to the success of the ROV, so significant design and effort went into its creation. Prior experience with finite-element analysis of pressure vessels showed that a thickness of at least 0.5cm was required to eliminate the potential for flexing or deformation at depth, which would defeat the lid seal. The thickness of the end plate was designed such that it would deform minimally when the screws were tightened, reducing the number of screws needed to provide a reliable seal. Six screws seal the canister to the lid, threading into welded tabs on the outside surface of the canister. The small number of bolts through the lid makes the canister very easy to open and close. The lid includes a variety of threaded holes to accommodate connectors and bulkhead penetrators, which seal against the lid using either O-rings or tapered pipe threads.

Design Note: Skippy MkII's pressure vessel used 36 bolts to maintain the lid seal and was extremely inconvenient to open and close. This incredibly time-consuming process was required to perform regular maintenance and troubleshooting on the ROV, and was a key factor in guiding the design of Aegir's pressure vessel.

Vehicle Frame



Purpose	Components and Features
Provide a rigid structure for attaching components while fitting within 75cm x 75cm hole in ice sheet.	<ul style="list-style-type: none"> ● Welded 1"x1" 1/16"T square aluminum tube ● Supports hardpoints for pressure vessels, thrusters, grippers, and other mission tools. ● Handles facilitate transfer to and from water.
<p>Overview: Aluminum was used because it is inexpensive, corrosion resistant and easily machineable. A central structural member provides an attachment point for the electronics canister. Vertical struts support the ascent thrusters and flotation, and provide a point to mount the vehicle transport handles.</p>	

Buoyancy and Ballast

Purpose	Components and Features
Equalize buoyant force and counter moments resulting from distribution of forces to keep ROV neutrally-buoyant and level.	<ul style="list-style-type: none"> ● Rigid polystyrene foam; shielded with epoxy to prevent damage to foam from wear-and-tear or pressure at depth. ● Steel rebar; encased in polymer coating to protect against corrosion and galvanic effects.
<p>Overview: The flotation blocks are bolted to the top rail of the frame and provide vehicle buoyancy. The electronics canister is a significant contributor to the ROV's overall buoyancy, so the floats are positioned to balance its off-center position. Coarse ballast is provided by rubber-coated rebar on bottom of frame. Fine ballast adjustment can be made with galvanized steel washers of various sizes.</p>	

Design note: Polystyrene dissolves in the presence of many paints and solvents, so care had to be taken to select coatings that would not damage the flotation blocks. Epoxy was ultimately chosen because it is inert, durable, and easily applicable as a liquid. Latex paint applied over the cured epoxy adds style and team spirit.

Waterproof Connections



SubConn connector pair



Threaded static penetrator

Watertight Connector A: SubConn Wet-Mateable Plug (IL4M, BH4F, MCOM8M, MCBH8F)

Purpose	Components and Features
Connect the ROV to tether for power and ethernet. Prevent intrusion of water into sensitive equipment.	<ul style="list-style-type: none"> ● Robust commercial-grade underwater connector ● Wet-mateable with proper lubrication ● Watertight to 1400 meters

Overview: Two SubConn electrical connectors link the tether to the ROV. One is dedicated to 48VDC and includes four conductors. The other is dedicated to Ethernet and includes eight conductors. Both connectors are wet-mateable, so the ROV can be safely submerged with the tether detached for testing. The connectors are lubricated with petroleum jelly before mating.

Watertight Connector B: Static Penetrator

Purpose	Components and Features
Provide connections from the ROV to cameras, lights and	<ul style="list-style-type: none"> ● Created from ¼" or ⅜" tapered-thread brass pipe fittings bored out to a constant diameter. ● Cables sealed with binary epoxy

Overview: The fittings are bored to a constant diameter on a lathe and cables are passed through the middle. Binary epoxy is applied in and around the end of the fitting corresponding to the wet side of the penetration. The tapered threads on the fittings are designed to seal when tightened, so applying torque when threading the fitting it into the bulkhead provides a reliable watertight seal. A variation on this design uses a brass compression fitting as an in-line cable connection.

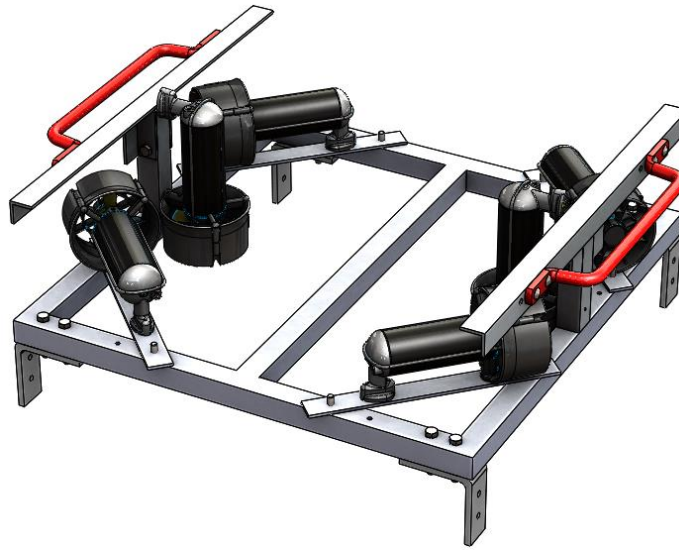
Watertight Connector C: Permanent Inline Soldered Connection

Purpose	Components and Features
Protect external cables from water.	<ul style="list-style-type: none"> ● Soldered splice sealed with binary epoxy and heat shrink

Overview: Many electrical connections do not need to be removable, and external cables are occasionally cut and spliced. Sealing the soldered joint with epoxy prevents water from penetrating inside the wire's insulation, and protecting the epoxy with heat shrink or self-vulcanizing tape prevents the hardened epoxy from cracking.

Propulsion Systems

Vectored Thrust Configuration



Purpose	Components and Features
<p>Allows the ROV to move in any planar direction, rotate, and move vertically.</p>	<ul style="list-style-type: none"> • 4 thrusters mounted at 45-degree angles relative to vehicle forward direction • 2 thrusters mounted vertically for ascent and descent. • Software algorithm determines power for each thruster based on desired resultant net thrust vectors.
<p>Overview: Previous experience showed that the ROV needed to be able to move laterally, especially when the mission task required collection of items or precision alignment with targets. The team determined that six thrusters would be needed to achieve the desired level of fine control. Four of the thrusters provide lateral motion and are angled at 45° relative to the ROV’s forward direction. By controlling individual thrusters’ power and direction, the ROV can be made to move in any lateral direction. This is particularly useful during missions requiring precision alignment of grippers or other tools; if the ROV is in the wrong orientation, it can move sideways or rotate to move into the correct alignment, which is much faster than backing off for another attempt. The remaining two thrusters are directed in line with the ROV’s vertical direction and move the ROV up and down. The net center of thrust of the vertical thrusters is approximately in line with the ROV’s center of mass, center of buoyancy, and center of drag, so the ROV</p>	

Design Note: There was considerable debate as to which mounting angle would be best for the planar thrusters. While a 30° thrust angle would give more power when moving forward and backward while allowing lateral motion, RHRT ultimately decided to use 45° angles because this simplified the control scheme and maximized Aegir’s turn rate.

SeaBotix BTD150 DC Thruster

Purpose	Components and Features
Provides variable thrust to move the ROV underwater.	<ul style="list-style-type: none"> • 12VDC sealed waterproof thruster • Max Rated Power: 23W • Maximum Thrust at 12V: 7.35N forward, 6.66N reverse
<p>Overview: SeaBotix thrusters are reliable and provide excellent fine control. The expense of purchasing COTS thrusters and the loss of the opportunity to design custom thrusters were balanced by the benefit of guaranteed drive functionality and the ability to focus on more advanced design features elsewhere.</p>	

Software

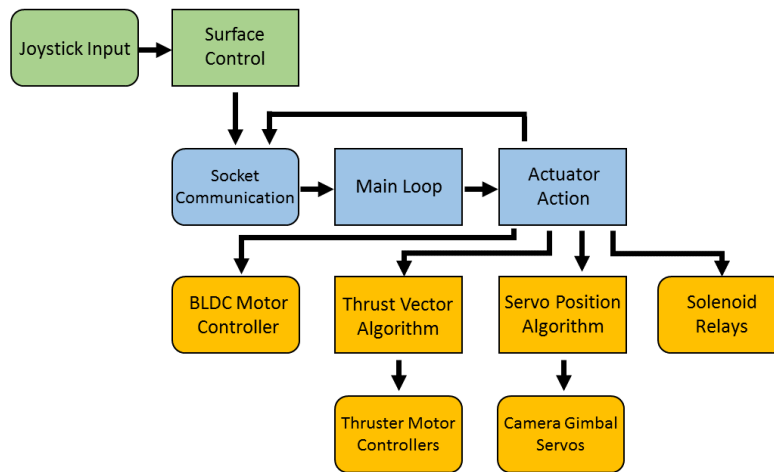


Figure 10: *Aegir* control software flowchart. Square nodes represent structures and handlers, round nodes represent inputs and actions.

Purpose	Components and Features
Allow remote communication with the vehicle while minimizing latency.	<ul style="list-style-type: none"> • Pilot’s surface station interface reads joystick input and displays sensor information. • Onboard the ROV, Beaglebone Black parses incoming data from surface to operate actuators and motors. • See Figure 10 for software function block diagram.
<p>Overview: The control station on the surface runs a program written in Python which takes input from the six axis joystick, packetize the data, and sends it to the ROV over an Ethernet network connection. Data flowing upstream is displayed in on the control console as required. In an example of code reuse, common functions are encapsulated into subroutines which can be called when needed, reducing the size of the program and making the code neater and more manageable. Transmission of camera data occurs separately from the vehicle communication program.</p>	

Power Supply and Distribution

Power Conversion System	
Purpose	Components and Features
Reliably distribute power to all of the electrical systems on the ROV. Cut power to any component that overdraws current to prevent damage to other systems.	<ul style="list-style-type: none"> • Multifunction Anderson connector allows use of compatible battery banks or other power supply systems as available. • 30A breaker and main power switch immediately following tether power connector. • 48VDC from tether passes through DC-DC converters • 12VDC for thrusters, cameras and light; 950W max output. • 5VDC for BeagleBone Black, IMU and servos; 200W max output. • Separate fuse systems for 12VDC and 5VDC circuits.
<p>Overview: Main vehicle power is sourced from an interchangeable 48VDC power supply located on the surface. Depending on the requirements of the mission this can be a portable battery bank or an inverter from wall power. A standard Anderson electrical connector allows the power supply to be quickly changed. The main vehicle power switch is located immediately downstream from the connector. It includes an integral 30A fast-blow circuit breaker.</p> <p>Upon entering the ROV the main power supply is split and stepped down to provide different voltages to the subsystems as required. The thrusters, cameras, and communication system run on 12VDC, which is provided by a pair of 48VDC-12VDC converters linked in parallel to provide sufficient power to run these systems. The Beaglebone Black and servo motors run at 5VDC, which is provided by a 48VDC-5VDC converter.</p> <p>For each level of voltage, every component is linked in parallel to a central distributor bus and fuse block. This prevents a general system failure if a single component draws too much power.</p>	
Tether	
Purpose	Components and Features
Supply electrical power and compressed air to the ROV. Provide a means of manually retrieving the ROV in case of system failure.	<ul style="list-style-type: none"> • 11 total conductors • 3 wires in power cable (1 power, 1 ground, 1 unused) • 8 wires in cat6e ethernet cable • 2 pneumatic lines (supply, exhaust)
<p>Overview: The tether includes a 1/25cm diameter soft-cell backer foam to make it neutrally buoyant. Tether elements are bundled with plastic cable wrap to prevent damage to the tether and to prevent entanglement with obstacles.</p>	

Design note: The power supply system was designed to handle a wide range of possible manipulators and attachments, so its capacity significantly exceeds Aegir's total draw at full power.

Onboard Control System

Single-Board Computer: Beaglebone Black

Purpose	Components and Features
Receive operator commands and send signals to downstream components.	<ul style="list-style-type: none"> Complete system-on-a-chip computer Embedded 1GHz ARM Cortex A8 processor 512MB RAM, 4GB onboard flash storage, 92 available pins

Overview: The Beaglebone Black receives data over Ethernet from the pilot station and sends out signals in several forms, including analog, serial, and PWM, to the vehicle's solenoids, motor controllers, and servos to throttle motors and move actuators as desired. In contrast to a microcontroller such as an Arduino, the Beaglebone functions as a flexible computer, so the operating software can be modified while the ROV is conducting its mission.

DC Motor Controller: Sabertooth 2x12

Purpose	Components and Features
Supply power to thrusters at specified throttle value.	<ul style="list-style-type: none"> Accepts a variety of input types, currently set for serial. 24VDC maximum input, 12A maximum output per motor

Overview: The control system includes a total of three Sabertooth controllers: one for the port thrusters, the second for starboard, and the third for vertical.

Brushless DC Motor Controller: MGM Compro TMM 7063-3

Purpose	Components and Features
Control brushless motor used in valve-turning attachment.	<ul style="list-style-type: none"> 12VDC-55VDC input, 70A max continuous current Controlled via PWM, signal range can be adjusted Full throttle range in both directions

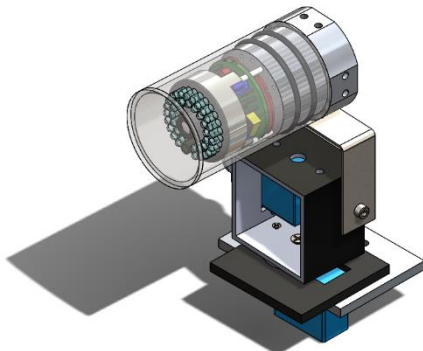
Overview: The TMM 7063-3 includes advanced firmware that allows tuning of its operating parameters based on mission requirements. Its throttle curve is currently specified to be linear and symmetric.

Ethernet Communication Network

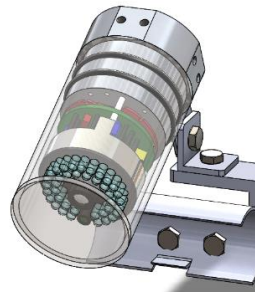
Purpose	Components and Features
Unify all system communication into a common network. Allows the ROV to be controlled through a laptop ethernet port.	<ul style="list-style-type: none"> 4-port Ethernet hub unifies cameras and Beaglebone Black Single CAT6 cable exits pressure vessel and runs to the surface along the tether. Creates an ad-hoc local area network that interfaces with all ROV systems.

Overview: Pilot control and sensor data has been standardized to use high-speed Ethernet, which reduces the number of cables in the tether and makes it very easy to connect to the vehicle on the surface.

Vision Systems



Primary camera with gimbal



Secondary camera with pivot

Configuration A: Primary Camera

Purpose	Components and Features
<p>The primary camera is the driver's main sensor for perceiving the environment around the ROV. It uses a servo gimbal to let the driver see beyond the normal field of view.</p>	<ul style="list-style-type: none"> ● COTS Ethernet security cameras modified for improved waterproofing and pressure resistance. ● 90° field of view underwater. ● Custom, acrylic housing sealed with dual O-rings ● 2-axis gimbal driven by Hitech HS-5646WP servos. ● 170-degree range of rotation in both axes

Overview: The camera is protected by a watertight pressure vessel with double O-ring seal. The aluminum end plug includes two square channels to hold the O-rings, as well as mounting points for the camera boards and flat hardpoints to facilitate attachment to the ROV. The acrylic housing tube was constructed from 6.35cm tube stock with a circular acrylic cap cemented to the end.

The camera assembly is attached to a 2-axis servo gimbal which gives a field of view of about 180 degrees along both axes. This gives the pilot access to a wide variety of viewing options. They can examine the seafloor by pitching the camera all the way down and looking past the front edge of the ROV's frame, and can also put each manipulator or tool in the center of the viewable area.

Under low light conditions the camera automatically switches to infrared mode and turns on an array of IR LEDs to illuminate the field of view.

Configuration B: Secondary Hot Stab Camera

Purpose	Components and Features
<p>Can be flexibly reoriented and remounted to provide an alternate perspective on mission tasks.</p>	<ul style="list-style-type: none"> ● Camera and enclosure identical to primary camera. ● Mounted on hinged joint to permit manual readjustment. ● Positioned above the hot stab hardpoint.

Overview: The secondary camera and its pressure vessel are identical to the primary camera system. The secondary camera lacks a servo gimbal, but it can be manually adjusted by team members to change its rotation. It can be positioned to look down the hot stab, which makes it easier to align with the hot stab port. It can also provide an oblique view of the gripper to facilitate picking up items.

Pneumatics Supply

Purpose	Components and Features
Provide pressurized air to operate the pneumatic gripper.	<ul style="list-style-type: none"> • Compressor and accumulator on surface stores air at 40psi. • 0.16cm pneumatic line runs along tether to onboard solenoid. • Relays used to actuate solenoid and feed pressure to bidirectional pneumatic cylinder.
<p>Overview: Air pressure is supplied by a portable shop compressor which includes an integral accumulator and regulator set to 40psi. Two air lines run along the tether; one supplies the pressurized air to the ROV and the other serves as an exhaust. A double-acting solenoid in the electronics canister actuates a single cylinder. A solenoid-based system was chosen because of its compact size and ease of use, as well as team members' prior experience with pneumatic systems.</p>	

Mission Tools

Parallel-Jaw Gripper (PeterGripper 5000GTX)



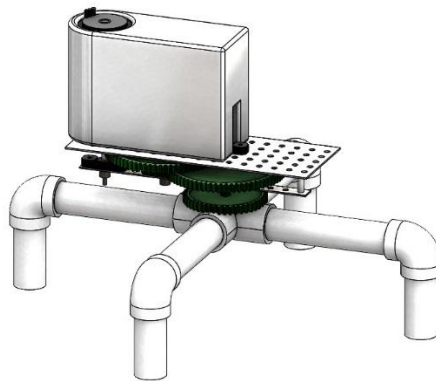
Purpose	Components and Features
Versatile primary manipulator. Used for picking up or operating most of the different objects encountered during a mission.	<ul style="list-style-type: none"> • Pneumatic double-action parallel gripper. • Maximum gripping diameter: 16cm • Constructed from waterjet-cut stainless steel and aluminum. • Gripping pads are polyurethane foam backed by delrin blocks.
<p>Overview: The gripper is constructed of corrosion-resistant materials, including stainless steel, aluminum, and Delrin plastic. The arms of the gripper are made of two layers of 14ga stainless steel separated by plastic spacers. This system is well suited to an underwater environment because it is inherently pressurized, unaffected by water, and able to provide a constant force. Gripping pads made of polyurethane foam conform to round and irregular objects making for a more stable hold. This foam was experimentally determined to offer the best coefficient of friction while submerged out of many other types of rubber and plastic.</p>	

Inertial Measurement Unit: Sparton GEDC-6E

Purpose	Components and Features
<p>Provides accurate real-time acceleration and heading data, which can be used to determine the absolute position of the vehicle and dimensional measurement of mission items.</p>	<ul style="list-style-type: none"> ● Includes gyroscope, accelerometer, and magnetometer. ● Built-in Kalman filter reduces gyroscope drift. ● Magnetometer can be calibrated using known global magnetic data to improve accuracy.
<p>Overview: A coordinate transformation algorithm lets the ROV track the position of a particular point on the vehicle, such as a gripper or a dedicated sensor probe, relative to a global reference frame. This can be used to measure the dimensions of objects and structures; by moving the probe from point to point on the object and noting the coordinates at each location, the displacement between points can be calculated and the length or height of the object can be determined. Angles can be measured by comparing displacement in the X-Y plane relative to the seafloor to the Z plane and performing trigonometry.</p>	

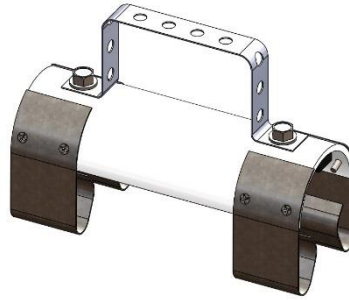
Design Note: Two Sparton GEDC-6E IMUs were donated to RHRT for use on an autonomous ground vehicle project. Use of an IMU had been previously conceived as a versatile tool for underwater measurement tasks, so the extra unit was installed in Aegir to implement this solution.

Valve-Turning Crank



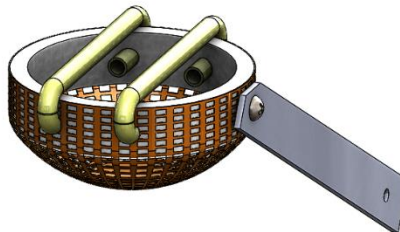
Purpose	Components and Features
<p>Allows valves to be quickly opened and closed without maneuvering the whole vehicle.</p>	<ul style="list-style-type: none"> ● 12VDC brushless motor ● 3D-printed motor housing and mounting block ● VEX plastic gear train provides 49:1 reduction ratio ● Turns at 1 rotation/s while submerged.
<p>Overview: The downward facing PVC spider contacts the cross shaped handles of the valves. A brushless DC motor rotates the spider through a plastic gear reduction system. The motor was waterproofed by sealing all wiring with binary epoxy and applying anticorrosive spray to the bearings.</p>	

Pipe Clamp



Purpose	Components and Features
Attach a tow line to a section of pipe so it can be removed to the surface.	<ul style="list-style-type: none"> • Springy jaws lock onto pipe during placement. • Handle serves as grab point. • Foam pad minimizes slipping on pipe after attachment.
<p>Overview: The clamp is pressed onto the pipe section until it engages. The spring clamps and foam backing provide friction which prevents the pipe from sliding during removal. The tow line attaches to the handle so that once the gripper releases the handle the section can be easily pulled to the surface.</p>	

Algae Collector



Purpose	Components and Features
Collect an algae sample from underneath the ice sheet.	<ul style="list-style-type: none"> • PVC ring with elastic retaining tube. • Operates without power or electronics.
<p>Overview: When the collector is pushed against the underside of the ice sheet, the algae sample is forced between the two strips of surgical tubing and held captive beneath them. A plastic net prevents the sample from escaping out the bottom of the collector. The algae collector is attached to the robot ahead of the front-left corner where it can be viewed using the camera at the center of the robot, and is removable with a single bolt when not in use.</p>	

Additional Mission Tools

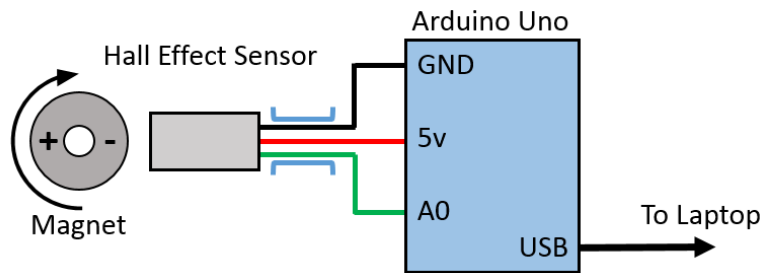


Figure 11: Flow sensor system interconnection diagram.

Flow Meter	
Purpose	Components and Features
Determines current flow rate by measuring the rotational speed of a propeller assembly.	<ul style="list-style-type: none"> • Propeller faces into current • Magnetic Hall effect sensor • See Figure 11 SID for detail.
<p>Overview: As the flowing water turns the rotor, it rotates a radially-polarized magnet. The change in the direction of the magnetic field switches a Hall effect sensor on and off, and the number of cycles per second is tracked by an Arduino on the surface. The software calculates the speed of the water using a conversion factor found experimentally during calibration testing in a flow tank. A vane keeps the propeller pointed into the flow.</p>	
Voltage Sensor	
Purpose	Components and Features
Enable the ROV pilot to measure the electric potential between conductors underwater, which shows if galvanic corrosion is taking place.	<ul style="list-style-type: none"> • Neodymium-alloy magnetic probes allow secure and consistent contact with electrical test points. • Leads run to Beaglebone Black analog input pin, which allows accurate measurement of very small voltage potentials.
<p>Overview: The high ion content of chlorinated water and seawater results in most of the electricity going through the water, leaving only a few millivolts of potential between the test leads. Integration with the Beaglebone Black is required to achieve the level of sensitivity required to definitively determine the presence of electrical potential between the contacts.</p>	
Hot Stab Hardpoint	
Purpose	Components and Features
Securely holds the hot stab during transport, insertion, and retrieval.	<ul style="list-style-type: none"> • Friction-based attachment system allows hot stab to pivot during insertion.
<p>Overview: The hot stab handle is inserted into the cradle and then zip tied into place. The inward facing tab provides enough resistance to keep the hot stab from rotating under its own weight but not so much that it cannot self-position as it is pushed into the angled pipe on the wellhead.</p>	

Project Cost

Table 2: *Aegir* final project expenditures.

* indicates reused component ^D indicates donated or reused component

Electronics	Count	Unit Cost	Total Cost
12VDC Relay	3	\$8.00	\$24.00
48VDC-12VDC converter (CUI Inc. NQB-468NMA-ANH)*	2	\$80.00	\$160.00
48VDC-5VDC converter (Vicor V48A5C400BL)*	1	\$60.00	\$60.00
Assorted wiring and connectors*	1	\$40.00	\$40.00
Beaglebone Black	1	\$54.95	\$54.95
Brushless DC Motor Controller*	1	\$230.00	\$230.00
Ethernet camera	2	\$150.00	\$300.00
Fuse box*	2	\$10.00	\$20.00
LED Array	1	\$54.00	\$54.00
NETGEAR ProSAFE FS105 Ethernet Bridge	1	\$29.99	\$29.99
Sabertooth 2x12 DC Motor Driver	3	\$80.00	\$240.00
Sparton GEDC-6E IMU ^D	1	\$1,600.00	\$1,600.00
SubConn Female Power (BH4F)	1	\$76.85	\$76.85
SubConn Female Ethernet (MCBH8F)	1	\$110.10	\$110.10
SubConn Male Ethernet (MCOM8M)	1	\$77.35	\$77.35
SubConn Male Power (IL4M)	1	\$42.30	\$42.30
Tether CAT6E Ethernet cable	1	\$60.00	\$60.00
Tether power cable	1	\$40.00	\$40.00
Subtotal			\$3,219.54
Thrusters and Motors	Count	Unit Cost	Total Cost
Bilge pump*	1	\$20.00	\$20.00
Brushless motor	1	\$30.00	\$30.00
SeaBotix Thruster	6	\$700.30	\$4,201.80
HS-5646WP Servo	2	\$60.00	\$120.00
Subtotal			\$4,371.80
Material And Hardware	Count	Unit Cost	Total Cost
0.25" aluminum plate	1	\$36.11	\$36.11
0.375" aluminum plate	1	\$37.79	\$37.79
1"x1" aluminum tube	3	\$17.91	\$53.73
1/4" brass fittings	12	\$1.50	\$18.00
2.5" aluminum circular stock	1	\$25.00	\$25.00
3.25" acrylic tube	1	\$42.17	\$42.17
3/8" brass fittings	8	\$2.50	\$20.00
Delrin rod	1	\$15.00	\$15.00
Epoxy	6	\$4.50	\$27.00
Handles	2	\$8.69	\$17.38
Magnet - axially polarized	4	\$2.00	\$8.00
Magnet - radially polarized	2	\$2.50	\$5.00
O-ring assortment	1	\$8.00	\$8.00
Polystyrene insulation foam	1	\$12.50	\$12.50
Red paint	1	\$6.00	\$6.00
Stainless steel sheet	1	\$40.82	\$40.82
Valve turner 3D print	1	\$17.00	\$17.00
Flowmeter 3D print	1	\$8.00	\$8.00
Flowmeter propeller	3	\$5.00	\$15.00
Subtotal			\$412.50

Pneumatic System		Count	Unit Cost	Total Cost
Solenoid		1	\$89.00	\$89.00
1/16" Tube		1	\$40.00	\$40.00
Cylinder		1	\$20.00	\$20.00
Barbed Fittings		20	\$0.75	\$15.00
Subtotal				\$164.00
Logistics and Administrative		Count	Unit Cost	Total Cost
International Registration		1	\$150.00	\$150.00
Airline Tickets		9	\$800.00 (avg)	\$7,200.00
International Lodging		7	\$240.00	\$1,680.00
ROV checked luggage fee		1	\$800.00	\$800.00
Subtotal				\$9,830.00
Total ROV Cost		Less Donated and Reused Items		Total Project Cost
\$8,167.84		\$6,097.84		\$15,947.84

Project Budget

Funding Source	Total Cost
Rockwell Collins (via RHRT all-team budget)	\$17,000.00
Rose-Hulman SGA	\$1,800.00
Subtotal	\$18,800.00

Projected Expenditures	Total Cost
SeaBotix Thrusters	\$4,200.00
Motor controllers	\$360.00
Pneumatic equipment	\$300.00
SubConn connectors	\$2,400.00
Cameras and sensors	\$700.00
Materials and hardware	\$1,820.00
Travel	\$8,000.00
Subtotal	\$17,780.00

Project Retrospective

Reflections

Over the course of the past year RHRT has made great strides in project management and planning. Throughout the build schedule the project leader maintained a common task list and schedule. This ensured that tasks could be assigned based on what was most important to the project and that members were constantly productive and effectively utilized. At the beginning of the year senior team members conducted on-the-job training with new member to get them up to speed on the types of tasks they would need to accomplish. This allowed the new team members to start contributing to the project early and gave them the skillset required to take on a significant portion of the workload later on.

Despite these strides there was still some project management areas which could be improved. Estimates for the completion time on various tasks often proved to be overly optimistic. For instance, the time planned for the development of tools such as the valve turner significantly undershot the actual development time. This caused the team to have trouble getting enough practice on the tasks which required these tools. There were also a few times during the year when the team hit a bottlenecks where the productivity of the team dramatically dropped as we waited for a single issue to be resolved. For example, problems with software

development and troubleshooting occasionally hindered vehicle testing once mechanical development was largely complete. More effectively assigning secondary tasks during these delays would have helped team members make more efficient use of their time.

Technical communication was another area which greatly improved during the year. The software written last year, which served as a basis for development this year due to common system architecture, had multiple poorly-documented and disjointed parts. This created problems for members learning software development, and for the team members who wrote the system last year and forgot important operational details. When the system was rewritten this year, we wrote internal documentation into the code and created a software operation manual for future reference.

The team also acquired a great deal of practice explaining the robot and its various systems to sponsors and key stakeholders. Our work bay in the Branam Innovation Center receives a lot of traffic from other project teams, VIPs, and prospective students, which provided a valuable learning opportunity on presenting a good overview of the design and focus on the important points without getting bogged down in minute details. It also showed the importance of tailoring the level of technical detail to the immediate audience. Many of the stakeholders we talked to were not engineers and would not have benefited from information that would be insightful to someone with a more technical background.

Future Plans

Camera latency is the biggest current problem with the *Aegir* system. The control scheme is currently open-loop, so feedback from the operator based on the camera image is required for positional control. With a half-second of camera lag it is very difficult to maneuver on the centimeter level. Switching from a digital camera system to an analog one would reduce this lag by eliminating intermediate processing steps as the camera signal makes its way to the surface. One problem will be minimizing signal interference that could disrupt the camera image, which could be solved by switching to a composite video signal transmitted over a fiber-optic cable.

Closing the control loop using our inertial measurement system would be another improvement to the system. Implementing this higher level of control automation would make the *Aegir* easier to control and reduce the pilot's workload, minimizing the negative impact of camera latency. If both of these improvements were implemented it would allow for much more precise movement by eliminating the need for constant operator feedback.

Power is also an issue with the current ROV. The SeaBotix thrusters are underpowered at 12VDC, so valuable time is spent moving between the surface and mission targets. One solution to this would be to increase the voltage sent to the thrusters to 18VDC or 24VDC, which is nearer to their rated voltage. Plans to implement this change on *Aegir* had to be put aside as more immediately important tasks took precedence, so it is very high on our list of modifications following the mission.

The current pneumatic parallel gripper is a significant improvement over the simple static hooks used previously, but it could be useful to develop a more complex manipulator arm. A 6-axis arm would provide a range of motion similar to a human arm. This would make it easier to accomplish precision tasks like picking up small objects or inserting bolts into holes. Two multiaxis arms working in parallel would allow for the completion of very complex tasks, and with potential improvements to communication latency ROV performance could approach that of a human diver.

Sponsors



Acknowledgements

Rose-Hulman Ventures, for the use of their waterjet and other equipment.
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