Robotics Club at the University of Central Florida: Design and Implementation of Ness AUV

John Millner, Nicholas Peters, Kenneth Richardson, Christopher Grenci, Jonathan Gambrell, John Geiger, Ryker Chute, Wyatt Hunt, Drew Langston, Ruben Albarracin, Matthew Boutelle

***Abstract*—Today's autonomous underwater vehicles (AUV) have an ever increasing set of challenges as technology continues to evolve. From underwater defense and reconnaissance, to object placement and retrieval, to mapping and communication, AUV capabilities are constantly being refined and expanded upon for future real-world applications. In response to this growth, the Robotics Club at the University of Central Florida introduces a novel AUV prototype called "Ness".**

The design philosophy for Ness is centered on complete modularity and ease of use. Ness consists of five modular base sections, two arms, and a rear auxiliary plane which can be easily exchanged or modified to fit future environments and mission profiles. Further, Ness's base system includes two inertial measurement units (IMU), a doppler velocity log (DVL), forward facing lidar, two forward facing cameras in a stereoscopic setup, upward and downward facing cameras, and hot-swappable batteries.

Ness is designed for short duration littoral type missions where high maneuverability and object interaction are desired. Ness can submerge up to 10 meters in salt, brackish, and fresh water environments for up to two hours in its base configuration. To fully test the capabilities of the AUV, Ness has entered the 19th annual AUVSI and ONR collegiate competition, RoboSub.

I. INTRODUCTION

From military defense to academic research, the underwater world presents many challenges that only autonomous unmanned underwater vehicles (AUVs) can accomplish. The Robotics Club at the University of Central Florida (UCF) proposes an AUV called Ness in an effort to progress research and offer a working platform in the area of AUV design.

The Association for Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) 19th annual RoboSub collegiate competition, provides an ideal testing ground to assess Ness's effectiveness and versatility as an AUV robotic platform. The RoboSub competition contains many challenges such as vertical and horizontal door opening, torpedo shooting, marker dropping, hydroacoustic localization, selective object retrieval and placement, and landmark based navigation. Based on these requirements, Ness is intended for short duration littoral type missions where high maneuverability and object interaction are desired.

Ness is in its first iteration, designed by a small and diverse team of undergraduate engineering and computer science students with limited experience in AUVs or the RoboSub competition. There are still many experiential challenges that Team Ness will face in further testing of Ness in real-world scenarios. With this in mind, the primary goal for the first generation of Ness will be gathering data, stress testing Ness, and competing in the RoboSub competition in order to improve the next generation's design and share the lessons learned from this year's challenge. Throughout the process of Ness's development, documentation has been continually written and shared online, along with open source software and hardware repositories displayed on our website to aid the AUV community of the challenges and success for this competition and project.

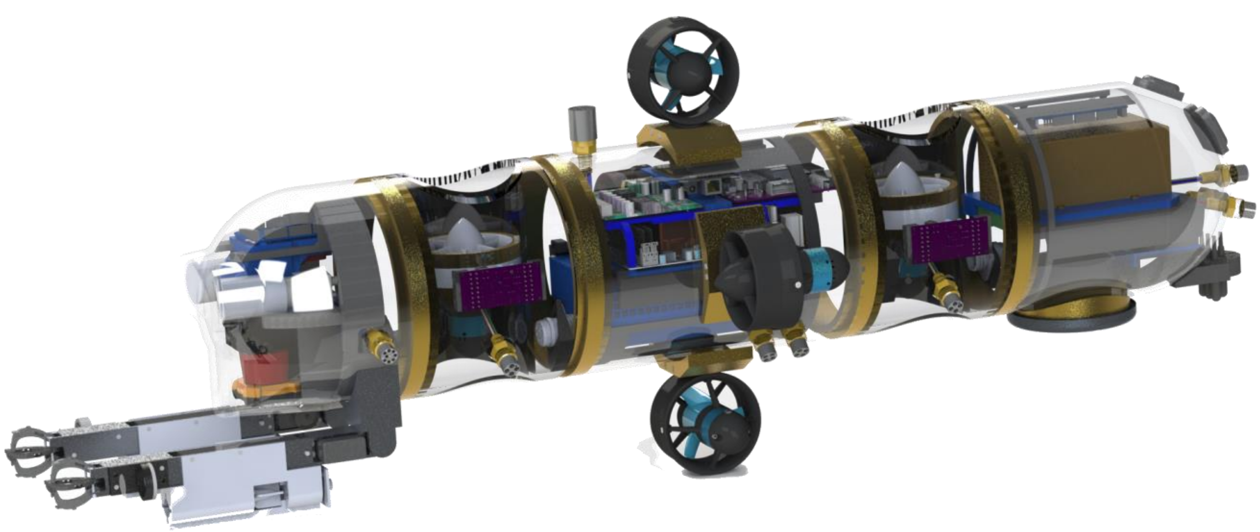


Figure 1: Ness

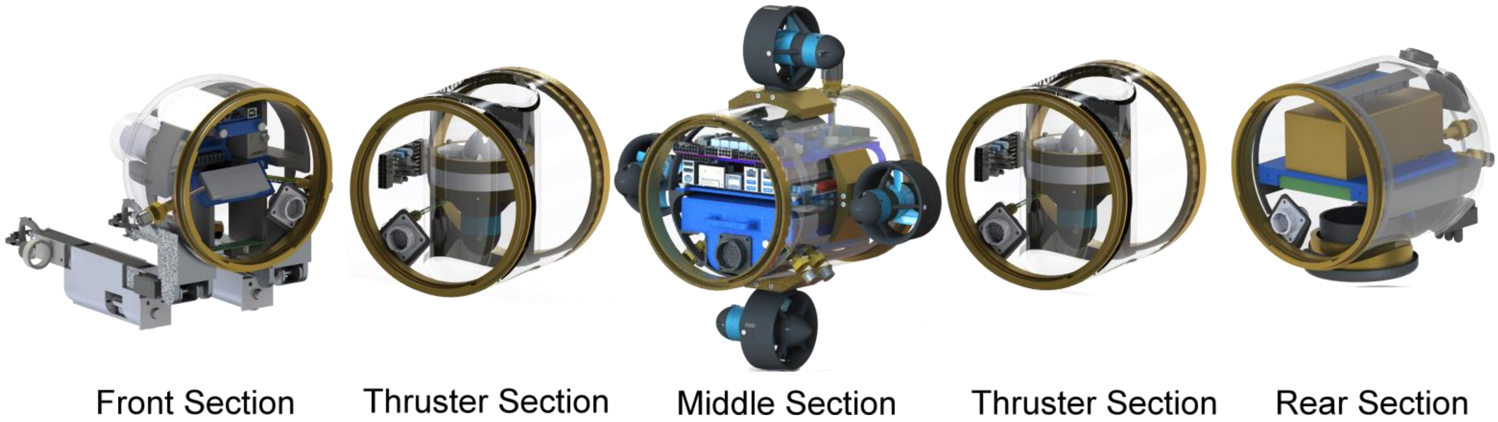


Figure 2: Sections

II. Design Strategy

Since the beginning of Project Ness, the first goal of the submarine is to have a simplistic and modular design capable of being easily constructed/deconstruction, modified, and understood.

To accomplish this, a small highly communicative team was created. The team created internal project deadlines and maintained a working schedule using Microsoft Projects with three major phases in the project: *Design Phase*, *Manufacturing Phase*, and *Testing Phase*. In *Design Phase*, weekly brainstorming sessions were carried out with the entire team to discuss mechanical, electrical, and software aspects and progress collectively between all subteams. Minutes were recorded for future reference and documentation generated as designs were finalized.

Once the *Design Phase* concluded, the team entered the *Manufacturing Phase* and began making the physical submarine, circuits, and the basic code outline and base software system. This was the longest phase and many parts were redesigned and improved as they were made and tested in the real world. When Ness was fully assembled *Testing Phase* began first with basic leak tests, and then full scale course mockups were created to test specific challenges in the RoboSub competition.

Ness was designed to handle the competition by utilizing the "poka-yoke" design principle throughout all aspects of the design in order to make the submarine user-proof and to reduce stress and human-error during testing and competition. These design influences are most noticeable in the opening/closing mechanisms of the submarine, color coded connectors, easy to change batteries, thruster placement, and sensor interface.

With a very limited amount of human resources and even less experiential resources, the primary goal of the first generation of Ness is to perfect movement and mechanical/electrical stability. Secondary goals are to gain proficiency in hydroacoustic localization and landmark based navigation. Tertiary goals are to simply attempt all other challenges. This was decided to create a focus on creating a robust system first, then a capable system, and finally if there is time, a well-rounded submarine, opposed to tackling the entire competition challenge repertoire all at once and become overwhelmed.

III. Hardware Design

During the initial planning stages of Ness, the team conducted in-depth research on past RoboSub teams, and other AUV and Remotely Operated Underwater Vehicle (ROV) designs and found what the team thought were good design ideas, and what could be improved upon in Ness's design. From this research, the main areas of attention were accessing the internal structures of the submarine, wire management, thruster configuration, and modularity. As a result, Ness was designed to have to have five discrete sections, where each is accessible through custom waterproof access points (called latches) and connected by a single uniquely keyed connector. Table 1 and Figure 2 describe and illustrate each section of the submarine and their dedicated tasks and functions.

Table 1: Ness Sectional Breakdown

Section	**Components**	**Tasks**
Front	Cameras, Lidar, IMU, Arms	Vision, Marker, Torpedo, Object Manipulation
Front Thruster	Pitch/elevation Thruster, Front Voltage Regulation	
Middle	Computing, Batteries, Low Level functions, Roll Yaw Strafe and Forward motion thrusters	Base Systems
Rear Thruster	Pitch/elevation Thruster, Rear Voltage Regulation	
Rear	DVL, IMU, Hydrophone, Switches, Depth sensor, Auxiliary Panel	Hydro acoustic localization, Navigation

Throughout the entire design process, it was critical to keep the design simplistic and fast to manufacture for every component. The team enlisted the help of Orange Technical College Mid Florida Campus to help machine parts of the hull, latches, and other parts of the submarine. All exterior aluminum parts on the hull have been anodized to prevent corrosion by salt or brackish water.

Ness heavily incorporated 3D printing technology to quickly and effectively make complex and customized internal structures and mounts (termed shelves and drawers) that would've been too time and cost expensive to make in traditional manufacturing methods. The concept of shelf-and-drawers system enables a user to quickly remove or install an entire system or component quickly and easily from the system so that maintenance or modifications can be performed.

A. Hull

The design of the hull was a compromise between buoyancy, internal part requirements, heat, make-ability, and cost. After many brainstorming and research sessions the final hull design was chosen. Using Dassault Systèmes SolidWorks, computational fluid dynamics (CFD) simulations were completed of the hull in flowing water, and a simplified heat transfer analysis of airflow within the submarine between heat producing electronics. In the design process Ness's hull evolved from a sphere, to a raindrop shape, to a cylinder, to a cylinder with spherical ends, and to the final design in Figure 3.

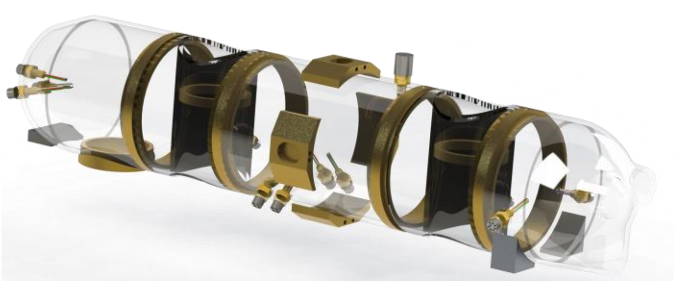


Figure 3: Hull

Featuring a total of five sections, three base sections and two thruster sections, the hull was finalized to have sections that each contained specialized tasks. The thruster sections feature a bisecting thruster tube where a vertical thruster is mounted for pitch and yaw movement. The front and rear sections contain custom molded features to better accommodate specific parts such as the stereoscopic camera setup in the front section and the control buttons in the rear.

The majority of the hull is created from off-the-shelf (OTS) cast acrylic tubing that are mated together by custom latches to form each section. On sections contain acrylic on acrylic mating, a combination of acrylic cement and a water resistant structural epoxy are used to create a structural and watertight bond.

Exterior electrical connectors for the hull were chosen after looking at what other teams and AUV/ROVs use as their connectors along with reviews on failures and ease-of-use. After much comparison Ness uses MacArtney SubConn Micro Circular connectors for all hull electrical connections for their ease-of-use, dependability, low maintenance, ability to be wet-mated, and easy installation, despite its high cost.

Many lessons were learned while attempting to mold the front and rear sections of the submarine. A polished aluminum mold is best for clear acrylic molding. Stretching will occur while molding and thusly the final product will be significantly thinner than the original sheet of acrylic used. Soft edges are critical to designing a vacuum formed mold. The best singular source for better understanding molding practices was given to the team by a member of Orange Technical College Mid Florida Campus, found in Reference 1. Also, as an important warning, isopropyl alcohol will very quickly craze and crack acrylic on contact.

B. Latches

The latches are a completely unique design created within the team that allows for an easy to machine, water proof access point that fully opens up the hull for accessibility and airflow. The latch is opened and closed by simply rotating the latch 45 degrees and is secured by a small non-load-bearing set screw. The latch is made waterproof by a combination of O-rings and silicon grease. The latches are attached to the acrylic hull by a water sealing structural epoxy. See Figure 4.

Figure 4: Latches

C. Arms

Designed to be a multi-year submission in the AUVSI RoboSub competition, the arms focus on being fully modular so that they can change each year as the competition creates

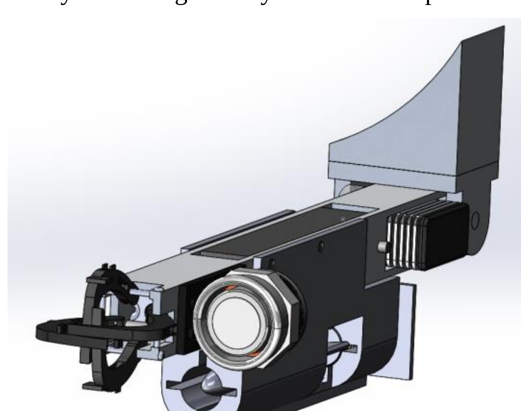


Figure 5: Arm

and removes tasks. Based on our observation of the previous years, the team identified the aspects of the competitions that are prone to change and decided to implement those tasks on the arm assemblies. In this year's completion, Ness's arms are able to open doors, fire torpedoes, drop markers, and pick up and place objects. The arms are easily removable for safe storage and any future improvements and changes. An arm can be viewed in Figure 5.

1. Torpedo

Both arms carry torpedo launching mechanisms. The 3D printed torpedoes are launched by a spring locking mechanism actuated by a servo. This servo rotates the torpedo within the housing until the fins line up with the matching slots in the housing and is then launched by the spring. The torpedoes have an average of 10 feet travel distance and the 3D printed housing in which they will be held until launch is attached to the middle section of the arm with a bolt and nut connection for accessibility. The team decided to not use any pressurized systems for the torpedo assembly to remove the possible failure modes of accidental-depressurization or running out of pressurized sources.

2. Markers

There are two simple ideas employed with the design of the markers. The markers must both be held in one hand from the beginning of the completion, and they should be designed so that they will fall straight down with no deviation. The team designed two markers that could be held in one hand from the fingers. Once the bin is found and uncovered with the other free hand, the arm holding the weights is moved to a vertical position where the markers are then dropped. The markers will be 3D printed to be manufactured with a profile that will easily glide through the water and have little resistance so that they fall straight down and avoid missing the bin. The markers will also have built in cavities so that weights can be added to them to make sure they have a low center of mass so they do not tumble as they fall.

3. Sensors

The sensor loadout of each arm consist of a violet colored laser to aid vision in locating the arms, a narrow beam sonar module to detect how far away the hand/torpedo module is from contact and feedback sensors from the linear actuator that control the extension of the hand, and then the servo that controls the angle of the arm. Careful selection of the components was made to use similar voltages and communication protocols to reduce the number of circuits needed to go through the hull.

4. Hands

Both of the arms on the sub have a custom designed three-pronged hand/claw as the end effector. Each of the fingers have multiple solid bodies (digits) and they are collapsible. This design takes into consideration the variable dimensions of the objects to be handled throughout the obstacle course. The fingers are held open by elastic strings on their outer side with the actuating tendons on their inner side. These tendons run down the arm past the laser diode mount to a linear actuator. This actuator has about 3 inches of maximum working distance and is located within the aluminum frame of the arm. All moving parts of the claws as well as the part that helps connect them to the aluminum part of the arm are 3D printed. The claws are attached to the plastic connector with a bolt and nut for easy removal and installation.

D. Internal Structures

The internal design required compact spacing and modularity. Many of the parts needed to be easily removable, yet still firmly held in place when secured. These unique structures are most easily created through the use of 3D printing. The team partnered with the UCF Machine Shop and Limbitless Solutions to print parts accurately using Stratasys Dimensions series 3D printers.

Each part is printed using acrylonitrile butadiene styrene (ABS). ABS was the best choice due to its relatively high deformation/glass transition temperature, along with its good resistance to repeated deformation and wear. ABS also enables the use of heat-set threaded inserts for screws, greatly increasing the longevity of the parts.

The forward, middle, and rear sections all follow a similar design motif. There is one central shelf which is epoxied to the outer acrylic shell. All hardware parts are secured to custom designed drawer pieces which slide into place on the epoxied shelves. The drawers are then constrained by thumb screws which allow tool free insertion and removal, this drawer/shelf configuration can be visualized in Figure 6.

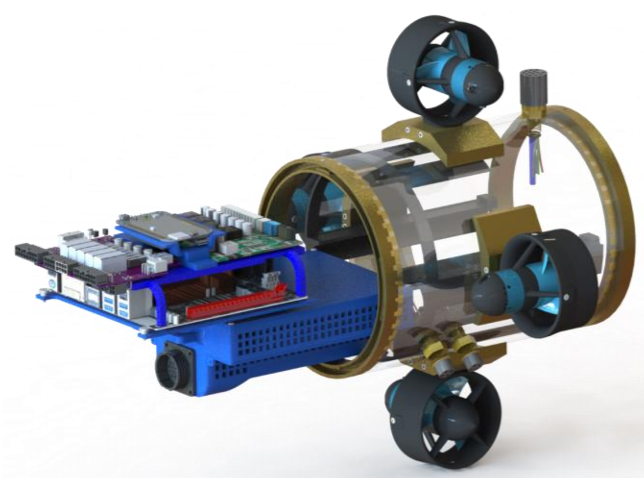


Figure 4: Drawers and shelves

E. Cases, Transportation Cart, and Sling

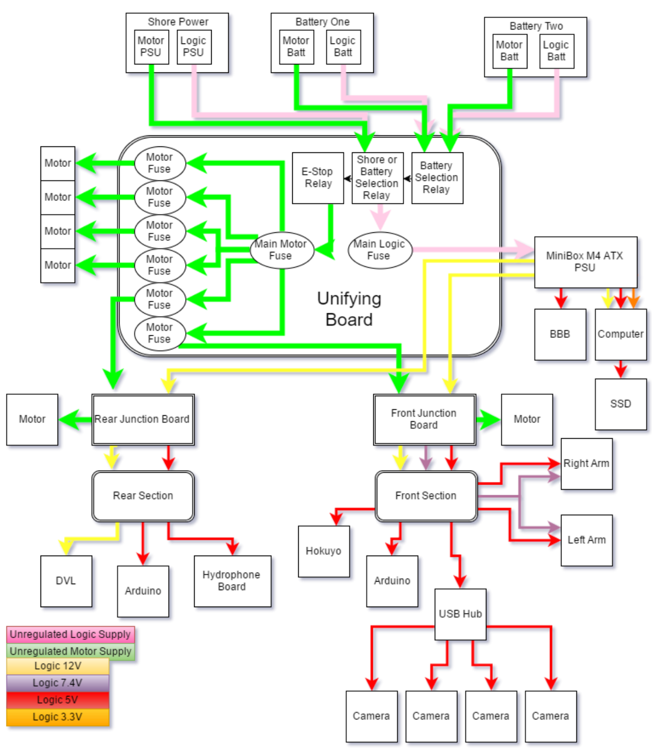
The case for Ness and the accompanying equipment had to protect all entities from the torture of shipment while remaining easily portable. Three separate cases were sponsored by SKB Cases, one for Ness, one for the batteries and the last for the supporting systems and field repair. Each has custom inserts to further protect each entity. Ethylene-vinyl acetate (EVA) foam was laser cut to ensure a snug fit for each section of the hull. Custom battery housings were 3D printed to lock the lithium ion batteries in place. In addition, no flammable materials were used to ensure safety during shipment. Each case is wheeled to make them easily portable even when filled to capacity.

The transportation cart and sling provides a stable platform for Ness when fully assembled. The sling and cart collapse down to fit in the lid of the large Ness case and can easily deploy by rising and securing the structure much like a EMT stretcher. The sling carries Ness both in the transportation cart during travel and has attachments for a crane to hook onto during deployment. The sling is made of a gripping rubber material to keep the sub firmly intact during field transportation, testing, and maintenance.

IV. Electrical Design

The electronics of Ness are centered around reducing human error by using color coded connectors and a minimizing the amount of connections overall. One of the team's biggest fears was the possibility of mating two wrong connectors and destroying sensors or other devices. To prevent this many different sizes of connectors were chosen, similar connectors contained unique keyings, and all connectors that could still be mated with one another were color coded.

Another method used to reduce human-error was by creating centralized PCBs that simplified hooking up the submarine and reduced the chance of a confusing rats nest being created. This was accomplished by a custom Unifying Board which acts as a centralized hub for all connections, custom junction boards within the thruster sections, and custom fuel gauge boards within each battery pack. To further reduce the number of connectors and boards each of these boards handle both power and logic circuitry. Figure 7 demonstrates our power structure. Figure 8 demonstrates our logic structure.



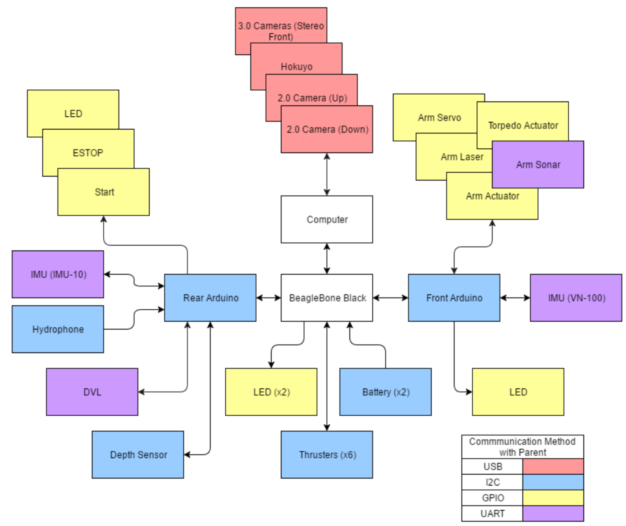


Figure 8: Logic structure

The electrical systems for the Logic based systems and the motors have been completely separated by using two different sets of batteries and using opto-couplers to communicate between the two systems. This separation is to prevent the logic systems (most notably the computer) from being interfered with by the motor system's rapid power fluctuations which can create instability and cause the computer to reboot.

Figure 7: Power structure

A. *Logic Shelf*

The Logic Shelf of Ness (Figure 9) is designed to contain everything required to run the computer and logic systems. By placing all these components in a unified location, including logic power systems, the computing unit can easily be taken out of the submarine for testing and repair if needed. The Logic Shelf contains a Mini-ITX motherboard running Ubuntu 14.04, with an Intel i7-6700T, a M2 PCIe SSD, a MiniBox M4 ATX DC PSU, a BeagleBone Black, and a custom Unifying Board. The Unifying Board shown in Figure 10 is designed to handle hot swapping the batteries, handling the emergency stop commands, turning on the computer, and transferring data from the motor and logic systems over a I²C bus.

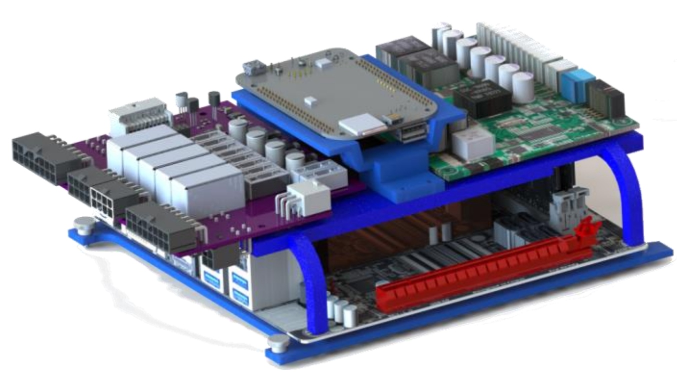


Figure 9: Logic Shelf

The GIGABYTE H170N-WIFI Mini-ITX motherboard was chosen for its built in ESD protection, moisture/humidity resistance, and two LAN ports, one used to communicate with the BeagleBone Black and the other to a shore tether for testing and debugging. The Intel i7-6700T was chosen for its high performance/efficiency ratio. The MiniBox M4 ATX PSU was chosen for its high efficiency in DC-DC conversion and its ability to communicate diagnostic information over USB.

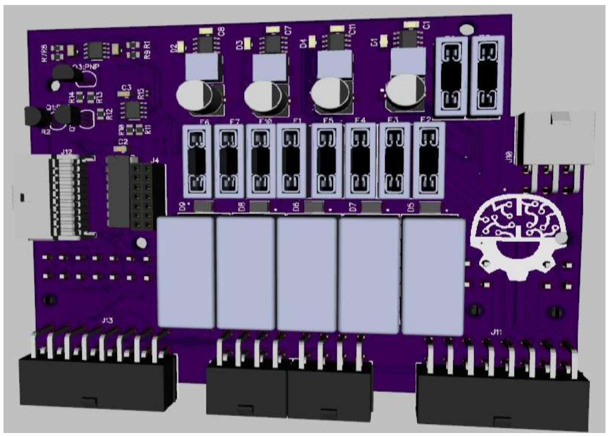


Figure 10: Unifying Board

B. Communication

Shown in Figure 8, the logic and communication structure of Ness is designed to be a hierarchal system structure where the main computer orders goals to a BeagleBone Black (BBB). The BBB then takes these goals and sends out lower level commands and requests for motors or sensor data through an I^2C bus connected to native sensors, motors and peripheral Arduinos. These peripheral Arduinos (one located in the front section, and one in the rear section) receive those commands and requests and act on them. With sensors hooked into the Arduino's various general purpose input and output (GPIO) ports the Arduino collects the relevant information and confirms that any commands were carried out and sends back a I^2C packet to the BBB which then gets parsed and returned to ROS for processing. This hierarchy is made to use the most efficient processor for the task at hand and reduce load on any one system. The use of Arduinos and BBBs allow for future expansion as there are many GPIO ports remaining.

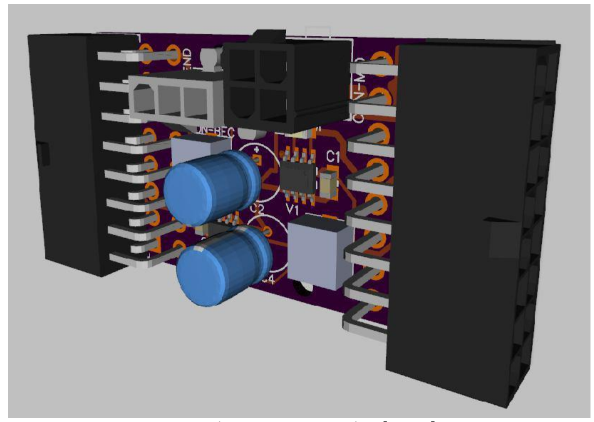


Figure 11: Junction board

C. Hydrophone

Ness uses an array of four TC-4013 hydrophone sensors in order to determine the distance and bearing to the pingers. The data is collected through the hydrophones and fed into an FPGA, where the time difference of arrival is calculated through Generalized Cross Correlation using Phase Angle Transform (GCC-PHAT). The time differences between hydrophones is then used to determine a likely area that the current pinger could be found. The FPGA outputs a vector to the rest of the sub that can be called upon when needed.

D. Batteries

Custom Battery Packs were made to power Ness's logic and motor systems. Two separated 4S 12.6Ah with OTS battery protection modules and a custom Fuel gauge each keep the sub powered for over 45 minutes under normal use, and up to two hours with low use. The fuel gauges communicate over I^2C for constant battery diagnostics including temperatures. The battery packs are contained within a 3D printed enclosure to keep them safe and portable. Three packs were made so that the submarine could operate perpetually (with battery changes) if need be.

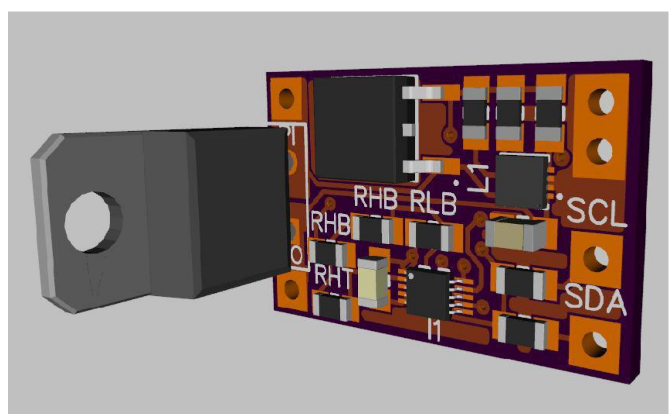


Figure 12: Fuel gauge

V. Software Design

All of the software systems in Ness depend on the Robot Operating System (ROS), which is a collection of software packages for robotic systems that is primarily used to abstract message passing between processes in a way that allows processes to pass data in the same manner if they are on the same machine or two different machines on a network. Additional ROS packages add capabilities like Kalman filters, SLAM, logging, and visualization that can be easily integrated into a system thanks to the message passing architecture.

Using ROS allows for high-level, computing-heavy tasks on the powerful main computer while allowing low-level hardware interface software to run on a BeagleBone Black connected on a network that has more suitable I/O hardware but less processing power. ROS makes the passing of messages over the network easy, flexible, and robust. Additional open-source ROS packages were taken advantage of to perform tasks like state estimation with an extended Kalman filter, which means that details of implementation can be skipped to focus on other parts of the system, as well as having more support available for common ROS packages than would be available for custom software.

A. Control

A constant stream of data is collected through all of Ness's sensors and filtered through an extended Kalman filter node in ROS which provides an estimation of its current state. Using the output from the state estimation the thruster controller node runs closed-loop PID control systems for each of Ness's six degrees of freedom. These control loops continuously calculate the speed for each of the thrusters in order maintain constant stability, as well as for perform any requested orientation changes or movements.

B. Navigation

Ness's navigation system depends on state estimation from an extended Kalman filter, and path planning implemented with the ROS MoveIt! Package. The MoveIt! package provides a *move_group* node which acts as a central point for the various robot control nodes and the extensions that MoveIt! provides. The *move_group* node also takes the URDF and SRDF files that describe the robot from the central ROS parameter server to ensure that it can work properly with full knowledge of the robot's state. Ness primarily uses MoveIt! for its interfaces to the Open Motion Planning Library (OPML), because OMPL does not directly concern itself with the specific details of the robot. This allows for easily creating simple motion plans for navigation while ensuring that all aspects of the robot are considered in the plan. Due to the relative sparseness of possible obstacles in the course, the path planning system is currently implemented in a way that does not take potential collisions into account.

The navigation node is implemented as a ROS Action Server and Action client pair. This ensures that only one navigation goal is running at a time, and provides a consistent means of handling new goals in a way that safely interrupts or continues the execution of existing goal. The navigation client node processes requests based on the current state of the mission planner and processes a navigation goal to be passed to the server. The navigation server takes the goal pose requests from the client and calculates the necessary thruster commands. If a new goal is requested it will either reject it and continue with the current goal, or preempt the current goal and proceed immediately to executing the new goal. The behavior chosen in this event is dependent on the current state of the mission planner, which is processed into a header value for the goal action message.

C. Mission Planner

Mission planning is based on the Python-based SMACH (State MACHine) library which allows for breaking down complex tasks into a hierarchy of simple actions called states. The state machine is a container for all possible states, with each individual state taking input data if applicable and executing a series of output commands and sensor readings. Based on the outcome of those readings the state then chooses what data to pass on and which state to execute next.

Ness's states are configured to control small individual components which allows for states to be reused among different tasks. For complex tasks a type of state called a Concurrence is used which allows for multiple states to be run concurrently. For instance, Ness can receive data from its cameras while simultaneously controlling its movement and manipulating its arms. The *smach_viewer* program is used to provide a state-flow diagram visualization of which state Ness is currently in and what data is being passed between states, which allows for detailed monitoring of what actions are currently being attempted and their outcomes.

D. Vision

Ness's vision system consists of a set of object-specific detectors managed by a single multiplexer node. The multiplexer node listens to the mission planner and is responsible for starting and stopping the various object detectors as well as passing them image data from the correct camera source and broadcasting it to the vehicle's ROS system. The multiplexer can also manage a set of ROS nodes that take input from the vehicle cameras over USB and broadcast it over ROS. These nodes can be started, stopped, or reconfigured to shed CPU load from unused camera feeds. Stopping object detectors not in use also helps free up CPU time for more the object detectors that are in use.

The object detectors use a combination of convolutional neural networks and more traditional thresholding and contouring operations to estimate the pose of objects in the camera's space and return it to the multiplexer node. The neural nets were trained using data shared by other teams from previous years, and were adapted from systems meant to detect facial keypoints in images. By using large datasets of real-world data, the neural net is trained to detect objects under conditions similar to those during competition. In the case of objects not present in previous events, threshold and contour based systems were used due to a lack of training data for machine learning systems.

VI. EXPERIMENTAL RESULTS & CONCLUSIONS

Ness is still in its Testing Stage as it nears the RoboSub competition which takes place in July 25-July 31 2016. Together the team has created a dependable and stable mechanical and electronic system. The team is still working hard to perfect software goals.

The team experienced a few difficulties, the largest being a small and overworked programming team and a five-month lull in funding while the United States of America Congress attempted to pass the 2016 Fiscal Year Spending Bill. At the time of writing this report Ness has only been able to be leak tested once, simulations have been carried out and as much testing as can be done out of water has been. Water-testing and course testing will start very soon, however internal deadlines have been passed from initial plans. A lack of experienced programmers and the lull in funding from government based sponsors severely hampered the progress of the team. Despite this, Ness is a soon-to-be capable platform that will be sure to exceed expectations, perform well at RoboSub, and contribute to future AUV robotics research!

A. Hardware

Overall, the mechanical and electrical design of Ness has successfully captured the goals set forth at the beginning of the project. The original goal set forth was to create a modular design which would allow easy integration of new parts as further improvements are designed.

B. Software

The software systems aboard Ness meets the basic goals of the project by using ROS to maintain a high degree of software modularity. Software modules can be swapped out with no recompilation of existing modules and minimal reconfiguration due to the way modules connect at runtime rather than compile time using ROS's message passing architecture. This will allow incorporating additional improvements in the future.

Efforts in the immediate future will mostly be towards increasing the efficiency and accuracy of navigation, as this is a primary goal for this iteration of Ness. Improvements will also be made towards refining object detection and improving performance on manipulator based tasks.

ACKNOWLEDGEMENTS

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We would also like to thank all of our sponsors who allowed this team to succeed and follow a passion. We could not have done this without you!

REFERENCE

[1] Multifab Incorporated (2009, June). Thermoforming Design Guidelines. [Online]. Available: http://www.multifab-inc.com/guidelines.pdf

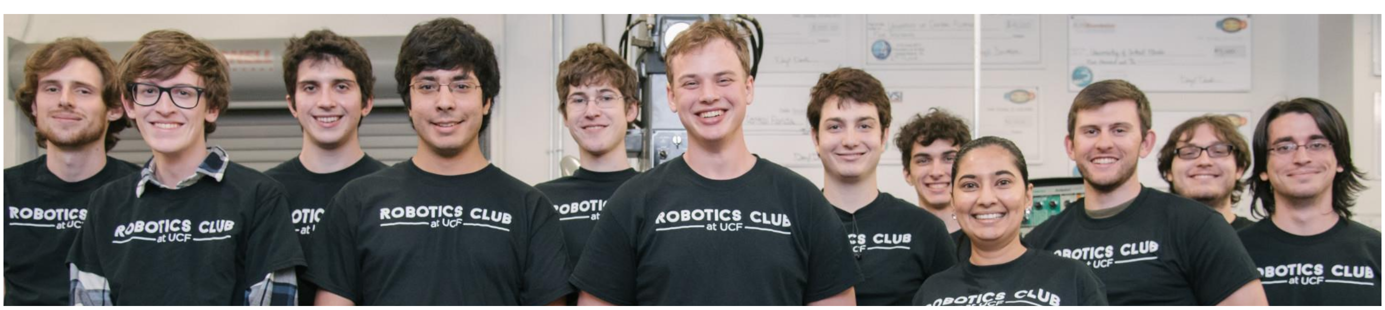

Figure 13: Team Ness