Cornell University Autonomous Underwater Vehicle: Design and Implementation of the Thor & Loki AUVs

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Abstract—**Thor & Loki are the new 2015-2016 CUAUV autonomous underwater vehicles (AUVs), designed by a team of 45 undergraduate students at Cornell University. Completed in a ten month design cycle, both vehicles were fully modeled using CAD software, extensively simulated with ANSYS, and manufactured almost entirely in-house. The designs of Thor and Loki draw heavily upon over 15 years of aggregate research and development to enhance autonomous underwater vehicle technology by CUAUV members.**

Notable new advancements include quick-maintenance sliding racks, four dynamically vectored thrusters, a revamped serial protocol supporting online code flashing, and a full software simulation system complete with an integrated physics engine, three-dimensional vehicle and environment visualization, and automated mission testing and verification. Thor and Loki's combined sensor suite totals four inertial measurement units (IMUs), five CMOS cameras (three forward, two downward), a Teledyne RDI Explorer Doppler Velocity Log, two depth sensors, two internal pressure sensors, one full and one partial hydrophones arrays, and a BlueView high-definition imaging sonar. Returning features include vacuum-assisted sealing, hot-swappable batteries, six degree-of-freedom control, and pneumatic actuator systems on both submarines.

I. Introduction

THE Cornell University Autonomous Underwater Vehicle team's primary objective is to design and build an autonomous underwater vehicle (AUV). The AUV is a cumulative product of many integral end-to-end projects that necessitate extensive hands-on experience, critical problem-solving skills, and interdisciplinary collaboration amongst students. Upon completing the vehicle in a ten month design cycle, CUAUV participates in the annual AUVSI Foundation and ONR International RoboSub Competition. The competition is held in late July at the TRANSDEC facility, part of SPAWAR Systems Center Pacific in San Diego, California.

RoboSub is designed to challenge student-built AUVs with an obstacle course that simulates real-world AUV missions such as accurate seafloor mapping, subsea infrastructure construction, and precise underwater object manipulation. RoboSub competition tasks range from shape and color recognition to torpedo firing and fine control of small objects. Each of these tasks must be completed by the vehicle autonomously (without any human interaction or control). Successfully completing such tasks requires accurate visual and acoustic detection of competition elements, fine-control navigation, obstacle avoidance, and object manipulation. In order to complete the task of building a vehicle that is capable of navigating all mission elements and meeting all requirements, CUAUV is divided into four subteams: mechanical, electrical, software and business/public-relations, each of which is divided further into project-specific working groups.

II. Design Overview

The 2015-2016 primary vehicle, Thor, and the 2015-2016 secondary vehicle, Loki, are both hovering, littoral-class AUVs designed primarily to compete in the RoboSub competition. Their designs, built on those of previous years, are similar to that of work or observation class remotely operated vehicles (ROVs), primarily targeting space-constrained complex functionality and fine-grained positional control.

Thor and Loki are designed to work in tandem to complete the RoboSub course faster and more reliably than would be possible with only a single submarine. An underwater acoustic communication system allows the submarines to transmit task status and submarine state back and forth in realtime as the mission progresses. This communications link can be used to allow the two submarines to share course state information (more accurate element positions based on new observations) and take over from one another should unexpected problems occur during mission execution.

III. Thor

Fig. 1: A SolidWorks rendering of CUAUV's 2016 primary vehicle, Thor

Thor is an improvement over CUAUV's previous vehicles in terms of fine control, robustness, and ease of assembly. Robustness was improved through more extensive electrical testing, a stiffer frame base, and a simulator to test mission code before the AUV was manufactured. Added space was strategically positioned for ease of assembly and testing of enclosures. Removable SEACON panels were added to decrease time and increase ease of electrical assembly and integration. Eight Blue Robotics brushless thrusters give Thor control over six degrees of freedom. The location of surge thrusters on extended arms improves stability in movement. The vehicle also includes a pneumatic actuator system that allows it to interact with its environment. Thor measures 43 inches in length, 35 inches in width, and 15 inches in height. Its dry weight is 81 pounds.

Custom electronic boards designed by students are isolated in the aft hull and work as interchangeable boards connecting to a central PCB backplane via PCI-express style card edge connectors. The vehicle is powered by two lithium-polymer batteries and contains modular power, sensor, and serial communication systems. A full onboard suite of visual, acoustic, inertial, and pressure sensors is used for navigation and data collection. The vehicle's software suite is run by an integrated computer with a quad-core hyperthreaded Intel i7 CPU, and is primarily composed of intercommunicating shared memory, serial, control, vision, and mission systems.

A. Mechanical Systems

Thor's mechanical system consists of the vehicle frame, upper hull, actuators, and external enclosures. The upper hull and external enclosures are responsible for protecting the electronic components from water, while the structure provides mounting points and protection for sensors, enclosures, and actuators. Assemblies are designed in SolidWorks, simulated using ANSYS finite element analysis (FEA) software, and then manufactured either manually or with the help of CNC machinery and computer-aided manufacturing (CAM) software (Pro/TOOLMAKER and FeatureCAM).

1) Frame: The frame defines the positions and orientations of each mechanical component in the vehicle, maintaining the structural integrity and rigidity of the vehicle and protecting delicate components. Intensive FEA was done on the frame to ensure that it would be able to protect all the components within. Thor's frame implements a modular method of component attachment. Water-jet cutting allowed for rapid manufacture of frame components and for speedy assembly and testing.

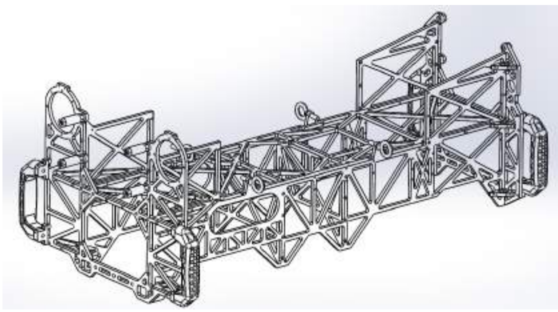

Fig. 2: Thor's frame.

Most of the components on the vehicle are screwed directly to the frame, requiring no extra mounting features. This saves weight, reduces complexity, and allows for efficient use of space. All components are placed such that the center of mass is at the relative center of the AUV. The frame emphasizes ease of use, manufacturing, and integration whilst remaining adaptable.

2) Upper Hull and Electronics Rack: Thor's upper hull is composed of two racks joined by a midcap, undersea connectors, the DVL transducer head, and two acrylic hull assemblies that protect the electronics. The fore rack contains all commercial off-the-shelf (COTS) components in the upper hull including the COM Express module, DVL electronics, and LCD display.

The aft rack contains all custom electronics linked together via an easily customizable backplane system. All boards slide into connectors via 3D printed rails. Both racks are mounted on easy to use, custom rails which allow the electronics to slide away from the midcap and the internal wiring to be reached and modified easily.

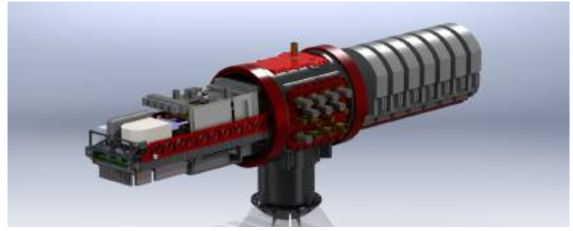

Fig. 3: Thor's fore and aft racks and midcap

All connections to the outside of the upper hull are made via SEACON connectors located on the midcap panels. These panels screw on to the midcap and allow parallel integration and maintenance of the SEACON. The midcap provides mounting for both the fore and aft racks, the DVL transducer head, and the sensor boom. Although difficult to manufacture, the midcap makes efficient use of space and material, while minimizing the risk of leaks. The two acrylic hulls slide over the cantilevered racks to provide sealing. Redundant sealing of the hulls as well as a slight vacuum within the upper hulls renders hull leak risk negligible.

3) Actuators: The actuators system is comprised of two torpedo launchers, two marker droppers, one active downward manipulator, and one passive forward manipulator. A 3000 psi paintball air tank regulated down to 100 psi serves as the air supply for the pneumatic portion of the system. Fourteen valves housed inside a custom enclosure regulate the flow of the compressed air to the rest of the actuator system. With this configuration, Thor can independently fire individual torpedoes and markers, and actively grab and release objects.

4) Torpedo Launcher and Marker Dropper: The torpedoes and markers are custom designed and cast projectiles made to travel accurately through the water. Torpedoes are propelled pneumatically and have a range of approximately 15 feet. Markers are held in place by magnets until a small air burst unseats them, after which their path downwards is held straight by large fins and heavy tips.

5) Active Grabbers: The grabber is responsible for grabbing the recovery objects. It

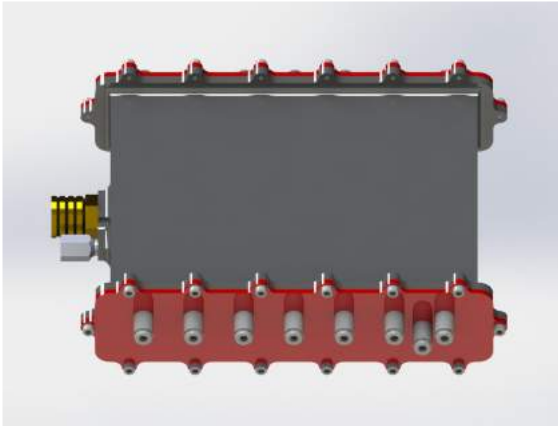

Fig. 4: Thor's solenoid valve enclosure

consists of a custom pneumatic linear piston connected to a scissor arm. On the end of the scissor arm is an array of electromagnets that can be turned on and off to magnetically grab the doubloons. The grabber is also capable of mounting a second custom piston. The piston is double-action: firing one valve closes the scissor arm and firing the other opens it.

Fig. 5: Thor's downward grabbers

6) Forward Manipulator: Thor features a passive forward manipulator utilized to remove covers on mission elements. Two X-shaped contact elements serve to automatically guide the handle of the lid into the sub's grasp. The contact elements contain a spring and Hall effect sensor system that serves as a touch sensor on the forward manipulator.

Fig. 6: One of Thor's forward manipulators

7) Thrusters: Propulsion is provided by eight Blue Robotics T200 brushless thrusters. Four thrusters are mounted on stepper-controlled mounts, enabling dynamically directed thrust vectoring for improved handling and speed. This vector thrust system provides 360 degree rotation of the four depth/surge thrusters. An CNC-machined enclosure houses a NEMA-23 stepper motor, a custom electronic driver PCB, a custom encoder to determine the direction of the thruster, a worm gear system, an encoder magnet, and an output shaft. Thor's thruster mounting scheme provides the vehicle with active control in all six degrees of freedom.

Fig. 7: One of Thor's vectored thrusters

8) External Enclosures: Thor's external enclosures contain various electrical systems located outside of the upper hull pressure vessel. These waterproof vessels isolate the systems from unwanted noise and allow for flexibility in the construction of the vehicle. Systems contained in external enclosures include the hydrophone acoustic system, kill switch, sensor boom, downward camera, and battery pods.

9) Hydrophones Enclosure: The hydrophones system is kept separate due to noise considerations. The enclosure was designed to be as light as possible and is constructed entirely out of aluminum to facilitate effective cooling. In addition, the piezoelectric elements of the hydrophones system are mounted directly to the wall of the enclosure, eliminating the need for a separate mount for the elements and keeping the system compact.

10) Sensor Boom: Some of the vehicle's sensors must be isolated from the electromagnetic noise caused by thrusters and other high-power electrical components. The sensor boom is mounted atop the midcap far from any other noise sources in order to maintain signal integrity. It contains a LORD MicroStrain 3DM-GX4-25 AHRS and a SparkFun MPU-9150.

11) Battery Pods: Two lithium-polymer batteries allow for hot-swap battery changes without powering down the AUV. Each battery pod features two SEACON connectors, one for monitoring temperature, and the other for charging and discharging the batteries. A DeepSea pressure relief valve also prevents any buildup of internal pressure, removing the danger of explosion due to out-gassing. The battery pod lids are latched to the hull with latches for quick battery removal and replacement.

Fig. 8: Thor's battery pod enclosure

B. Electrical Systems

The electrical subteam designed and populated custom circuit boards with the assistance of various schematic and PCB software packages. The dual-hull design of the vehicle emphasizes the strategic placement of electronics and wire management by dividing COTS devices from custom electronic boards. As a result of this and improved PCB back-plane usage, electrical connections are optimized between boards inside the hull, external enclosures, and sensors exterior to the upper hull.

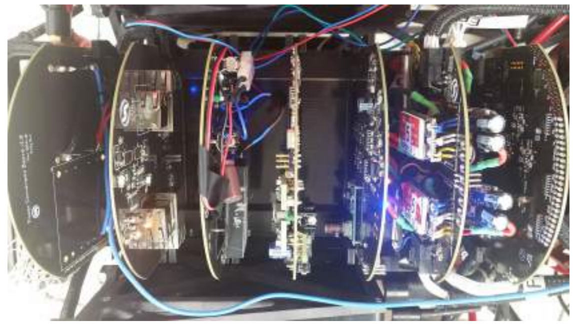

Fig. 9: The redesigned aft-rack back-plane

1) Power System: Thor's electrical systems supply up to two hours of reliable power throughout the vehicle and provide an interface between the on-board computer and all sensors and peripheral devices. The power to run Thor is provided by two Advance Energy 8000 mAh lithium-polymer batteries. To facilitate use of the vehicle on shore, a bench power station has been developed to power the sub from a standard AC power source. The input power sourced from the two batteries is routed through the merge board, which combines the two power sources to provide a single power rail for the vehicle. To ensure nominal and equal discharge from both battery packs, the merge board constantly compares the voltages and drains power from the battery with higher potential.

In order to ensure reliably regulated power, the power distribution board provides the electrical system with isolated power rails at +5, +12, +24, and +48 volts. The board measures power use from each channel and passes these statistics to the computer. In the case of excessive current draw, the computer has the ability to shut down the corresponding port to prevent potential damage to the components.

2) Serial Communication: The serial board is the interface between the computer and the various sensors and custom-designed boards.

It allows sixteen devices to communicate via RS-232 serial through two USB connections to the computer. The RS-232 protocol was chosen because of noise tolerance and ease of use and deployment.

Fig. 10: The serial board implementation featuring the back-plane edge connectors

3) CAN Bus: The CAN protocol is used to communicate with each of the four vector thrust modules. CAN was chosen over RS-232 because all the connected devices share only two communication wires. This allows the connection to all the vector thrust modules to be identical and allows connections to be swapped without effect. Each board is issued a unique device ID to enable individual vector thrust control.

4) Thruster Control: Each of the eight thrusters is controlled by a custom brushless module, contained within the main hull. Each board contains a microcontroller to communicate with a primary thruster board. To abide by safety regulations, all thruster modules, vector thrust modules and the actuator board can be halted either by hardware switch or software.

5) Vectorized Thruster Control: Each vector thrust module contains a stepper motor and a custom controller board. This board contains two H-bridges to drive a bi-polar stepper motor and communicates with the computer over the CAN bus. The board shares a connection interface with the other vector thruster modules, simplifying connections and allowing the devices to be swapped without software remapping.

6) Actuator Control: The actuator board controls the solenoids necessary for all of the pneumatic manipulators on the sub. The actuator board accepts commands to control the solenoids and an additional two DC motors or one stepper motor through communication with the computer using an isolated serial line.

7) Sensor Interface: The General Purpose Input Output (GPIO) board has multiple ports to read and write analog and digital inputs to and from sensors. It is primarily designed to provide the electrical system with extra modularity, as there is often a need to add sensors or electrical devices later in the design process. In addition to reading measurements from the depth sensor, GPIO monitors internal pressure of the vehicle to ensure that partial vacuum is maintained. GPIO also contains a custom designed Power Over Ethernet (POE) injector for powering our two forward cameras.

C. Sensors

In order to autonomously navigate through the competition course, Thor is equipped with two main classes of sensors: sensors to observe the vehicle's external environment, and sensors to determine the vehicle's state. Visual recognition and navigation tasks in TRANSDEC are successfully identified using two forward cameras and one downward camera, and high-definition imaging sonar, while the pinger-localized tasks are handled by the hydrophones system using a passive acoustic array. The state of the vehicle is measured using inertial measurement units (IMUs), compasses, a depth sensor, a Doppler Velocity Log (DVL).

1) Hydrophone Array: Thor's hydrophone system uses three Reson TC-4013 piezoelectric elements to detect incoming acoustic waves. The design was optimized for functionality and affordability utilizing a microcontroller and custom analog filtering to interpret the element data. The hydrophone system accurately calculates the heading and elevation of a pinger relative to the vehicle within one degree. The hydrophone system has also been extended to stream data over Ethernet to the vehicle's main computer which hosts a platform for real time acoustic debugging and finer tuning of the overall system.

In tandem to pinger tracking, the hydrophone system enables acoustic based communication and data transfer between Thor and Loki. One of the piezoelectric elements serves to both transmit and receive acoustic signals. Reliable communication is vital for multi-vehicle performance. Transmission data includes vehicle and element positions, mission task completion status, and vehicle state information.

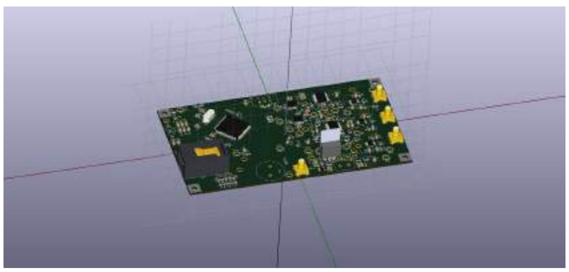

Fig. 11: The hydrophone system board implementation, featured in both Thor and Loki

The hydrophones system consists of three main components: the Ethernet-based communication to the computer, the transmit (amplifier) channel, and the three receive based channels. The transmit channel is created by using an onboard digital-analog converter (DAC) to create an output frequency, a 40V rail-to-rail amplifier, and an output transducer connection. The board communicates with the sub computer via an Ethernet port (using an ethernet phy and IP stack), and transmits raw time domain data to the computer for processing. The computer is used to control the receive gain settings, output frequencies, and several miscellaneous board settings. Data transfer is facilitated via a simple frequency-shift keying communication scheme, and is implemented onboard, which can be fine tuned via software's shared memory system. An improvement upon the previous version of this system was to run an IIR filter for each frequency we care to look at (in the 25 - 40 kHz range) instead of running continuous FFTs, thus decreasing computational complexity by about O(n). Thus, we have managed to simplify the identification of frequency and phase tracking to determine the direction of the pinger.

2) Orientation: A combination of IMUs and compasses measure the vehicle's acceleration, velocity, angular velocity, and spatial orientation. The orientation sensors on the vehicle are a MicroStrain 3DM-GX4-25 AHRS and a SparkFun MPU-9150. An MSI Ultra-stable 300 pressure sensor measures the depth of the vehicle.

3) Doppler Velocity Log: The Teledyne RDI Explorer Doppler Velocity Log (DVL) provides accurate three-dimensional velocity data. This information is used in conjunction with the other sensors to provide closed-loop vehicle control.

D. Software

All of Thor's higher level functionality, including autonomous completion of mission tasks, is achieved through the vehicle's software system. The software stack is built upon the Debian GNU/Linux operating system and includes a custom shared memory state synchronization system, a serial daemon for communication with the majority of the electrical boards, multithreaded vision, model-based control, localization, simulation, and abstract task/mission systems. Our custom software is primarily written in C++ and Python, with certain subsystems in Scheme and Haskell.

1) Computer: Thor's software is run on an Intel Core i7-4700 Haswell quad core processor hosted by a Connect Tech COM Express type 6 carrier board along with an ADLINK Express-HL module, using a 256GB mSATA solid state drive (SSD). The computer is connected dockside through a custom Gigabit Ethernet tether. A USB chip 802.11 adapter attached to the computer provides short-range wireless connection capabilities.

2) Shared Memory: The shared memory system (SHM) provides a centralized interface for communicating the state of the vehicle between all running processes, electronic subsystems, and users controlling the vehicle. SHM is a custom system built upon POSIX shared memory, providing thread- and process-safe variable updates and notifications. Various elements of the vehicle state are stored in and read from shared memory. These shared variables can be accessed by all of the components of the software system concurrently, which allows for simple communication among the various daemons. Bindings to SHM, most of which interface with the C bindings through foreign function interfaces, are available for Python, Scheme, Haskell, OCaml, and Go.

3) Serial Daemon: The serial daemon is responsible for syncing variables between the main computer and the electrical boards which control thrusters, actuators, sensors, and other devices. The serial daemon allows the computer to query the subs environment and control the subs behavior. Programs running on the computer, such as the controller and various missions, write values to variables in SHM which are then written to devices by seriald. Likewise, when devices modify their internal variables, seriald reads their values and writes them to corresponding values in SHM, allowing programs on the main computer to access them. The serial daemon enables any number of devices to read from and write to any number of SHM variables across any number of SHM groups.

4) Unscented Kalman Filter: Both submarines feature an Unscented Kalman filter which processes orientation data, in conjunction with a standard Kalman filter for position. By using the unscented Kalman transform, the orientation filter is able to heavily reduce the complexity of processing nonlinear systems, while still generating accurately filtered output. The use of the unscented filter allows us to use highly nonlinear quaternions to represent orientation, which do not suffer from the same limitations as traditional Euler angles (i.e. gimbal locking). This allows for a much more robust controller and overall enhanced stability for the vehicle.

5) Positional Controller: Positional controls (closing on absolute north and east positions) are achieved by a new navigational layer, which works by writing desires to the existing velocity-based controller in a way that simulates positional control. In order to implement positional control on top of velocity, a simple PID loop is used, which transforms positional error into a desired velocity. This design also makes it easy to enable optimizations; by default, the positional controller automatically controls submarine heading, orienting the sub in such a way as to produce the maximum possible thrust towards the desired destination.

6) Vision: Our vision-processing system is designed to give the vehicle up-to-date and accurate data about the surrounding mission elements. A daemon for each camera captures and passes raw camera frame data through an undistortion filter when necessary. This camera data is then passed into shared memory for concurrent processing by each vision module. The camera daemons and vision modules are entirely modular, so that we can run any combination of modules on either live data or replayed logs. Undistorted data is then analyzed using a combination of adaptive color thresholding, Canny edge detection, contour analysis, Hu moment characterization, and neural-network based classification. Thor possesses two IDS-uEye-5250CP Gigabit ethernet forward cameras, operating in stereo, and a downward-facing IDS-uEye-6250CP Gigabit ethernet camera for perception of mission elements located below the submarine.

Interprocess communication within the vision system has been significantly updated since last year. Instead of using sockets to dispatch images, we now use a set of shared memory blocks protected by read-write locks, with condition variables to ensure that vision modules get notified of new frames as quickly as possible. This system allows us to reach near the speed of threading with the modularity of having entirely separate vision modules and capture sources. We also revamped our vision

GUI to be served through a webserver, instead of X-forwarded from the sub. This let us offload a lot of the performance hit of the vision GUI to the clients, and allows for multiple simultaneous clients to view diagnostic output from vision modules.

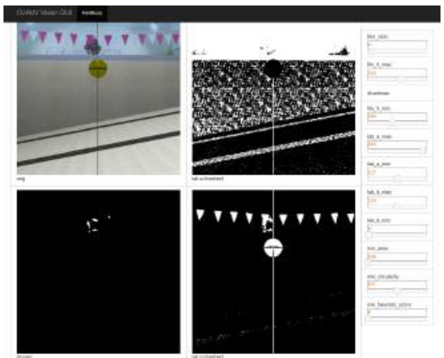

Fig. 12: Vision display/tuning GUI

7) Vision Tuning: A vision tuning system enables fast, real-time adjustments to the vision parameters. The vision tuning user interface shows the results of intermediate steps and makes it easy to see the outcomes of changes as they are made, allowing us to rapidly iterate upon our vision analysis algorithms. Each mission element has its own independent vision module. This allows for multiple modules to be run in parallel.

8) Vehicle Logging: The logging system captures the full shared-memory of the vehicle during mission runs. Furthermore, a log playback utility allows the software team to simulate the vehicle with real mission data and perform additional debugging and development out of the water. This system helps isolate bugs which only occur rarely. The software stack features a set of scripts which automatically upload all vehicle logs to CUAUV's networked server at the end of pooltests for later debugging.

9) Mission System: Missions, the highest level of control code, are implemented in a functionally-inspired Python interface that splits vehicle goals into discrete, reusable tasks. This framework allows for direct control of code execution without sacrificing ease of reasoning. Tasks are created in a simple functional style and can be composed to create various new useful tasks. The simplest combinators used are "Sequential" and "Concurrent" which run tasks in a serial or parallel fashion respectively.

10) Mission Simulation: A fast and extensible networked simulator, written in C++ with an integrated physics engine, is used to rapidly test mission logic against specifications. Mission tests, which verify successful task postconditions (e.g. ramming a buoy) given specified preconditions (sub position, buoy position, vision error, etc.) are scripted in Scheme and run mission code directly. The core simulator interfaces with our existing shared memory subsystem, so simulated missions can be run without modification.

11) Visualization: The visualization engine allows for easy viewing of simulations and submarine missions, and can be fed by sensor input during live runs to observe submarine orientation and movement. Our automated mission testing engine, Peacock, interfaces with our visualization software to provide instant feedback. In addition, simulated images provide an endless stream of testing data for our vision algorithms.

12) ASLAM: In order to accurately navigate between various elements during a run, our sub constructs a dynamically generated map of objects within the pool, updating the estimated positions of each object and the submarine as the mission proceeds and the submarine observes mission elements in various positions. ASLAM utilizes a version of Sebastian Thrun's published FastSLAM algorithm, adapted to the three-dimensional positional space of the submarine.

13) Control: Using continuously collected and filtered vehicle state data, Thor and Loki both have precise and accurate vehicle control for all six degrees of freedom: surge, sway, heave, yaw, pitch, and roll. The vehicles use an empirically tuned PID controller for each degree of freedom along with a passive force

Fig. 13: CUAUV's visualizer running a mission simulation (skybox taken from pool photo)

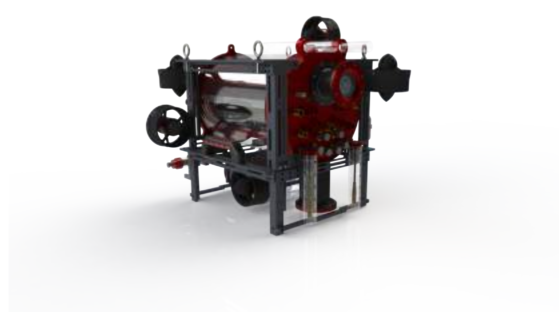

Fig. 14: A SolidWorks rendering of CUAUV's 2016 secondary vehicle, Loki

model and continuous optimization. The moment of inertia tensor of the vehicle is estimated from CAD to allow for better movement predictions. Using this system, Thor can compensate for any drag and buoyancy forces, even at non-trivial pitch and roll angles. The control system enables high-level mission code to set desired values for the velocity, depth, heading, pitch, and roll.

E. Mission Feedback and Diagnostics

Thor features an onboard computer-controlled color LCD display to provide visual feedback of the vehicle's current status, which enables continuous monitoring of mission progress during untethered runs. This allows for quick and easy reporting of vehicle information without the need for a computer, and is especially useful for system diagnostics, internal pressure monitoring, vehicle trimming, and thruster testing.

IV. Loki

A. Mechanical Systems

Loki's mechanical system consists of the vehicle frame, upper hull, actuators, and external enclosures. The upper hull is a single hull design and protects the electronic components from water, while the frame provides mounting points and protection for sensors, enclosures, and actuators. Assemblies for Loki were also designed in SolidWorks, simulated using ANSYS FEA software, and then manufactured either manually or with the help of CNC machinery and computer-aided manufacturing (CAM) software (Pro/TOOLMAKER and FeatureCAM). Manufacturing for Loki was primarily aimed towards manual machining for simplicity. Loki measures 21 inches in length, 18 inches in width, and 17 inches in height. Its dry weight is 33 pounds.

1) Frame: The frame defines the positions and orientations of each mechanical component in the vehicle, maintaining the structural integrity and rigidity of the vehicle and protecting delicate components. Intensive FEA was done on the frame to ensure that it would be able to support the weight of the system and protect the internal sensors and enclosures.

Loki's frame consists of modular aluminum L-channels with material strategically removed for weight savings while maintaining structural integrity. The channels are easily screwed together to create the overall structure with mounting locations.

2) Upper Hull and Electronics Rack: Loki's upper hull is composed of a single rack attached to a CNC-machined end cap, the undersea connectors, the lithium polymer battery, and an acrylic hull assembly that protects the electronics.

Fig. 15: A Solidworks rendering of Loki's frame

The rack consists of all the commercial components, including a single forward camera and an Intel NUC computer, as well as the custom electronics boards and the 12V lithium polymer battery. The rack is comprised of aluminum trusses and Delrin rails that connect two aluminum bulkheads. The boards either slide into the Delrin trusses or are mounted via screws. All the boards connect to the SEACON connectors on the fore cap. The battery is also housed within the racks and rests upon Delrin rails with Velcro strips to secure it in place. The aft cap has a hole with a removable aluminum plug to allow for quick battery swapping without removing the entire hull.

Fig. 16: A SolidWorks rendering of Loki's UHPV

The fore cap provides mounting for the rack, the depth sensor, the forward camera, the downward camera, and the piezoelectric element. It also provides both sealing and mounting to the forward and downward camera enclosures which protect the cameras. In-house CNC machining of the front end cap allows for minimizing weight while maximizing strength. All connections to the outside of the upper hull are made via SEACON connectors located on the fore cap. An acrylic hull is epoxied to an aluminum collar and a CNC-machined aluminum aft cap. The collar uses a double bore seal for redundant sealing of the main electronics. The redundant sealing of the hulls as well as a slight vacuum within the hull renders hull leak risk negligible.

3) Actuators: Loki's actuators system is comprised of two torpedo launchers, two marker droppers, a passive downward manipulator, and one passive forward manipulator. A CO_2 cartridge regulated down to 100 psi serves as the CO_2 supply for the pneumatic portion of the system. Four two-way valves housed inside a custom, CNC-machined aluminum enclosure regulate the flow of the CO_2 to the rest of the actuators system. The lid of the enclosure acts as the manifold for the valves. The smaller CO_2 cartridge and the minimum number of valves allows for the actuators system on Loki to be much smaller than its counterpart on Thor.

Fig. 17: A SolidWorks rendering of Loki's solenoid valve enclosure

4) Downward Manipulator: Loki's downward manipulator consists of a static aluminum arm whose position can be manually changed so that it does not interfere when Loki is out of the water. On the end of the arm is an attached X-shaped contact element which helps hook on to objects underneath the sub in order to move them.

5) Forward Manipulator: Loki features a passive forward manipulator, very similar to

Thor's, which is utilized to remove covers on mission elements. Two X-shaped contact elements serve to automatically guide the handle of the lid into the sub's grasp. The contact elements contain a spring and Hall effect sensor system that serves as a touch sensor on the forward manipulator. The arm of the forward manipulator mounts directly to Lokis frame.

Fig. 18: A SolidWorks rendering of Loki's forward manipulator

6) Thrusters: Propulsion is provided by six Blue Robotics T100 brushless thrusters: two surge, two depth, and two sway. Loki's thruster mounting scheme provides the vehicle with active control in all six degrees of freedom.

7) External Enclosures: Loki's external enclosures contain various electrical systems located outside of the upper hull pressure vessel. These waterproof vessels isolate the systems from unwanted noise and allow for flexibility in the construction of the vehicle. Systems contained in external enclosures include the kill switch and the sensor boom.

8) Sensor Boom: Similar to Thor, some of Loki's sensors must be isolated from the electromagnetic noise caused by thrusters and other high-powered electrical components. It contains a LORD MicroStrain 3DM-GX1 AHRS and a Sparkfun MPU-9150. Loki's sensor boom is a manually manufactured enclosure as opposed to Thor's CNC-machined enclosure.

B. Electrical Systems

Loki's electrical systems feature a miniaturized version of Thor's electrical system, providing reliable power throughout the vehicle and interfacing between the on-board computer and all sensors and peripherals within Loki.

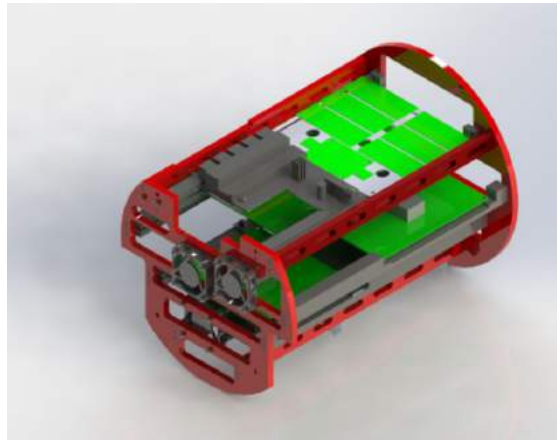

Fig. 19: Loki's legacy electronics rack

Due to Loki's simplicity, a board-to-board, direct wiring system is implemented. The design is similar to designs from years prior to Gemini (prior to 2013).

1) Power System: Loki is powered by one Advance Energy 12 volt 8000 mAh lithium polymer battery, which gives the vehicle approximately two hours of run-time. In order to maintain constant up-time while testing, Loki utilizes hot-swappable batteries, allowing for quick battery changes that do not require a full system reboot. To facilitate use of the vehicle on shore, a bench power station has been developed to power the sub from a standard AC power source. The input power from the two hot-swappable battery ports is routed through the power distribution board.

In order to ensure reliable regulated power, the power distribution board provides the electrical system with isolated power rails at +5 and +12 volts. The board measures power use from each port and provides these statistics to the computer. In the case of excessive current draw, the computer has the ability to shut down the corresponding port to prevent potential damage to the components.

2) Serial Communication: The actuator-sensor-serial (actusensor) board interfaces between the computer and the various sensors and custom-designed boards. It allows up to eight devices to communicate via RS-232 serial through one USB connection to the main computer.

3) Thruster Control: Each of Loki's six thrusters is controlled by an brushless ESC, contained within the main hull. A primary thruster board interfaces between the computer and each of the ESCs. Each ESC utilizes a pulse-width modulated (PWM) signal from the thruster board to determine the brushless motor's desired state.

4) Actuator Control: The actuator-sensor (actusensor) board controls the solenoid necessary for all of the pneumatic manipulators on the sub. The actusensor board also accepts commands to control the solenoids and an addition DC motor through communication with the computer using an isolated serial line.

5) Sensor Interface: The GPIO functionality of Thor is implemented within the actusensor board. The board primarily communicates with internal pressure, depth, and internal temperature sensors.

C. Sensors

Loki features one forward and one downward camera. The state of the vehicle is measured using inertial measurement units (IMUs), compasses, and a depth sensor. To communicate with Thor, the hydrophone system acts as a receiving and transmitting acoustic communication platform between the two vehicles.

1) Acoustic Communication: The acoustic communication system enables acoustic based communication/data transfer between Loki and another vehicle (Thor). A single Reson TC-4013 piezoelectric element transmits and receives acoustic signals. Loki's hydrophone system contains the exact same implementation as Thor's, but the two extra receive channels are not implemented.

2) Orientation: A combination of IMUs and compasses measures the vehicle's acceleration, angular velocity, and spatial orientation. The orientation sensors on the vehicle are a LORD MicroStrain 3DM-GX1 AHRS and a SparkFun MPU-9150. A Blue Robotics Bar30 High-Resolution 300m Depth/Pressure Sensor measures the depth of the vehicle.

D. Software

Loki possesses an identical software stack to Thor. Runtime-loaded configuration files encapsulate the differences between vehicles behind a unified abstraction layer. Mission, vision, control, navigation, and SLAM daemons likewise run continuously on Loki. Our simulation engine can simulate the control characteristics of both vehicles, so that missions can be tested on one sub or the other by changing a few configuration variables.

Loki's lack of a DVL makes navigation difficult. As a result, we use a more sophisticated velocity estimation algorithm based on sparse optical flow. First, features are detected in Loki's downcam using Shi-Tomasi corner detection. Next, the features are tracked via Lucas-Kanade optical flow. The bottom of the pool is assumed to be planar. Given the orientation and depth information from the sub, the features in the image plane can be traced to the pool floor. Their displacements relative to the camera can be used to deduce the velocity of the vehicle relative to the pool floor. New features are detected periodically as old ones leave the view of the downward facing camera.

V. Vehicle Status and Testing

Thor and Loki are both now in the pool testing phase. Prior to vehicle assembly, the mechanical systems were thoroughly leak tested, and the electrical systems were bench tested. The first in-water control test took place in late spring (the end of March for Thor, the end of April for Loki). Testing to prepare both subs for the RoboSub competition is still underway in various Cornell aquatic facilities.

Acknowledgments

CUAUV would like to thank all the individuals who have supported us over the past

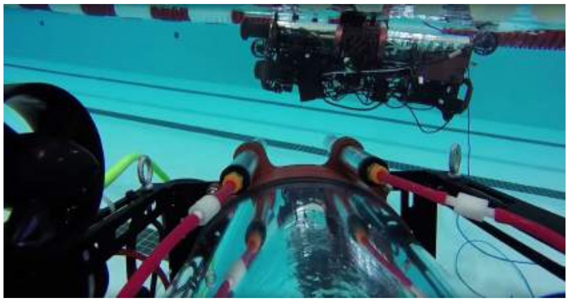

Fig. 20: Thor, as viewed from a GoPro camera mounted on Loki, at a pool test in progress

year, including Cornell's MAE, ECE, ORIE, and CS departments, and Cornell alumni who have supplied our team with needed lab space, materials, tools, and funding.

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Fig. 21: The 2015-2016 CUAUV team with Thor and Loki