Abstract—The CUAUV Ragnarök is a new littoral autonomous underwater vehicle (AUV) developed by a team of undergraduate students at Cornell University. Built in a ten month design cycle, the vehicle was fully modeled using CAD software and manufactured almost entirely in-house. With a number of new innovations, Ragnarök presents a stronger, lighter, and more agile platform with increased capabilities over previous vehicles. New advancements include a stronger yet extremely light frame, an improved electrical system, and significant software changes which yield improved mission reliability and robustness. Ragnarök’s sensor suite includes three color cameras, compasses, inertial measurement units (IMUs), a Teledyne RDI Explorer Doppler velocity log, a depth sensor, an internal pressure sensor, and a hydrophone array. Returning features include the single-hull cantilevered electronics rack, a vacuum-assisted sealing system, hot-swappable battery pods, pneumatic actuators, unified serial communications, and flexible mission software architecture.

I. INTRODUCTION

The Cornell University Autonomous Underwater Vehicle team’s main objective is to design and build an autonomous underwater vehicle (AUV) for the annual AUVSI and ONR International RoboSub Competition. The competition is held in July at the TRANSDEC facility, part of SPAWAR Systems Center Pacific in San Diego, California. The competition is designed to challenge student-built AUVs with tasks that simulate real-world missions. These tasks include visual and acoustic detection of competition elements, navigation, obstacle avoidance, and object manipulation tasks. Competition elements range from shape and color recognition to torpedo firing and turning a steering wheel. Each of these tasks must be completed by the vehicle independent of human control or interaction.

In order to complete the task of building a vehicle that is capable of completing all mission tasks and meeting all requirements, the team is divided into Mechanical, Electrical, Software and Business/PR subteams.

II. DESIGN OVERVIEW

The 2012-2013 vehicle, Ragnarök, is a hovering, littoral-class AUV designed primarily to compete in the AUVSI/ONR RoboSub competition. The design is similar to that of work or observation class remotely operated vehicles (ROVs), designed for high functionality and fine-grained positional control. This design was selected to best meet the challenges set forth by the competition.

Ragnarök is an improvement over previous vehicles in robustness, weight, and ease of assembly. The robustness was improved through more extensive electrical testing and rigorous
finite element analysis (FEA) and extensive use of computer numerical control (CNC) machining on the mechanical system. The vehicle was made easier to assemble by reducing the number of mechanical components, and by reducing the internal wiring by introducing blind-mate connectors between the boards inside the vehicle and the connector end cap.

The vehicle measures 39 inches in length, 22 inches in width, and 21 inches in height. Its dry weight is 80 pounds. Ragnarök features a single hull with integrated camera enclosures and a frame inspired by aerospace design. It has six thrusters which give it control over five degrees of freedom and a top speed of 0.6 m/s. The vehicle includes a pneumatic actuator system that allows it to interact with its environment. A full sensor suite of visual, acoustic, inertial, and pressure sensors is also on-board for use in navigation and data collection. The vehicle is powered by two six-cell lithium-polymer batteries, and contains a modular power, sensor, and serial communication system. The vehicle’s software is run on-board with a quad-core Intel processor. The software is built upon shared memory, serial, control, vision, and mission systems.

III. Mechanical Systems

Ragnarök’s mechanical systems consist of the vehicle structure, upper hull, actuators, and external enclosures. The upper hull and external enclosures are responsible for sealing the electronic components and protecting them from water, while the structure provides mounting points and protection for all of the sensors and enclosures.

A. 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. This year’s frame will act as an excellent testbed for some radical changes in the overall vehicle’s design, which includes a new Explorer Doppler velocity log (DVL), and the additions of a new fully sealed valve enclosure and servo enclosure. The frame emphasizes ease of manufacturing and integration, ease of use, options for modification, and backwards compatibility.

Most of the components on the vehicle are screwed directly to the vehicle, requiring no extra mounting features, which saves weight, reduces complexity, holds components more securely, and makes assembly and disassembly easier. All components were placed such that the center of mass is in between each pair of thruster shrouds, minimizing the amount of additional trimming required. A new feature to Ragnarök includes guards for the strafing thrusters, preventing wires from cluttering the area.
B. Upper Hull and Electronics Rack

Ragnarök’s upper hull is composed of a connector end cap, a forward-sealing collar, and a rear end cap, all connected by an acrylic cylinder. The hull assembly slides over the electronics rack and attaches to the main end cap with a bore and a secondary face seal. The three cameras use bore seals and face seals to seal directly to the hull, avoiding the need for external FireWire cabling. All three camera enclosures are intended to be lightweight, but durable at depth while providing a wide viewing angle. SEACON connectors pass through the connector end cap to provide an interface to external devices. Ragnarök’s wet-mate Ethernet tether is very accessible on the starboard side of the front end cap, allowing easy switching between tethered and untethered mission runs.

C. Actuators

The actuators system is a pneumatic system comprised of two torpedo launchers, two marker droppers, an active grabber, and a modified servo. A 3000 psi paintball air tank serves as the air supply for the entire system. The pressure is then regulated to 100 psi. Eight valves, housed inside an integrated valve enclosure and manifold, pass air from the solenoid valves to the rest of the actuators system. With this configuration, Ragnarök can independently fire both torpedoes and both markers and can actively grab and release an object.

1) Torpedo Launcher and Marker Dropper: The torpedoes and markers (see Figure 5) are custom designed and cast projectiles, made to travel accurately through the water. The torpedoes are propelled pneumatically and have a range of approximately 15 feet. The markers are also fired pneumatically, and are held in place by magnets until a small air burst unseats them. The markers then fall, guided by large fins and heavy tips.

2) Active Grabber: The active grabber is responsible for grabbing the recovery object. The grabber consists of two pneumatic linear cylinders connected to a pair of jaws (see Figure 6). The cylinders are double-action, so firing one set of valves closes the jaws, and firing another set opens them.

3) Servo Enclosure: A new feature to Ragnarök is a servo enclosure, which houses and seals an HS-645MG servo. Rotary arms are...
mated with the servo and the enclosure system and allow for a fine-controlled forward manipulator. The enclosure is also designed to be versatile for other uses, such as grabbing. The servo can also be modified to allow for continuous rotation.

4) Thrusters: Propulsion is provided by six brushed-motor, commercial, off-the-shelf (COTS) thrusters. Two thrusters are oriented in each of the main vehicle axes: surge, sway, and heave. The surge thrusters are VideoRay GTO 3 thrusters while the sway and heave thrusters are SeaBotix BD150 thrusters. This mounting scheme provides the vehicle with control in the three linear degrees of freedom, as well as pitch and yaw. Ragnarök also features the capability for alternative thruster mounting configuration, allowing for two additional SeaBotix thrusters to be mounted vertically if needed.

D. External Enclosures

Ragnarök’s external pressure vessels 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 pressure vessels include the hydrophones passive acoustic system, kill switch, sensor boom, DVL enclosure, and battery pods.

1) DVL Enclosure: The DVL enclosure (see Figure 7) is a custom enclosure that houses and protects the new Teledyne RDI Explorer DVL. It is designed to have redundant sealing, as well as to be as lightweight and compact as possible. It features an aluminum hull that houses the DVL electronics, as well as an aluminum “elbow” that joins the hull with the transducer head, and allows for cabling to pass between the two. The enclosure fits conveniently into Ragnarök’s frame, with the transducer located below the vehicle’s center of rotation.

2) Hydrophones Enclosure: The hydrophones system is kept separate for electrical isolation and ease of removal for testing. The enclosure was designed to be as light as possible using ANSYS FEA software, and is constructed entirely out of aluminum to facilitate cooling of the hot electrical components on the board. In addition, the piezoelectric elements for the hydrophones system are easily mounted and disassembled, allowing for easy testing of different element arrangements.

3) Sensor Boom: Some of the vehicle’s sensors must be isolated from the electromagnetic noise caused by the thrusters. The sensor
boom is a entirely non-metal pressure vessel, designed to maintain signal integrity, and mounted near the top of the vehicle far from any other noise sources. It contains the MicroStrain 3DM-GX1 IMU and passes its signal to the main hull via a SEACON connector.

4) Battery Pods: The current battery pod enclosures are entirely out of aluminum (see Figure 8). Each pod features two SEACON underwater connectors, one for charging and balancing the batteries within, and the other for discharging the batteries. A DeepSea pressure relief valve also prevents any buildup of internal pressure, removing the danger of explosion due to outgassing. The aluminum hull of the enclosure seals to two aluminum end caps. The first is outfitted with connectors, and the other features a display board cast in clear epoxy which indicates remaining charge. Each pod also contains a battery pod management board to protect the battery pack.

Fig. 8: Ragnarök’s battery pod enclosures

IV. ELECTRICAL SYSTEMS

Ragnarök’s electrical systems provide the vehicle with power and an interface between the computer and the other COTS devices. Nearly all of the boards are custom designed and populated in-house. Many boards contain a custom-coded microcontroller to interface with the computer.

Ragnarök features a backpanel to which boards blind-mate. This allows for improved wire management for electrical interfaces between boards inside the hull, external enclosures, and sensors exterior to the upper hull. This reduces the number of wires routed through the sub and decreases the amount of time it takes to maintain the electrical system.

A. Power System

The power to run Ragnarök is provided by two Thunder Power lithium polymer batteries which give the vehicle a run time of about 1.5 hours. These batteries are hot-swappable, which means the vehicle can be kept running while the batteries are changed. To facilitate extensive use of the vehicle on shore, a bench power box has been developed to power the sub from a standard AC power source. Custom circuit boards in the battery pods monitor the battery charge and shut off the packs to prevent over-discharge of the batteries.

All incoming power to the vehicle is routed through the merge board, which combines up to two power sources to provide a single power rail for the vehicle. The merge board draws from both batteries equally to ensure they are discharged evenly.

The power rail from the merge board is passed both to the high-power or noisy components, and to the sensor power board for regulation and isolation. The sensor power board provides the electrical system with isolated power rails at +5, +12, and +24 Volts (see Figure 9).

It also measures power use from each port and passes these statistics to the computer. Furthermore, the computer has the ability to control the status of each port, shutting it down if necessary.

One new development in Ragnarök is the addition of four bright LED strips controlled via a new LED control board. (see Figure 10). The LED control board takes input from Ragnarök’s software via serial and controls the LED strips, using them as visual indicators of the vehicle’s status. This is especially important during untethered runs, as the software team can monitor the mission progress at a glance.
B. Serial Communication

The serial board is the interface between the computer and the various sensors and custom-designed boards. The serial board allows fourteen devices to communicate via RS-232 serial through a single USB connection. The RS-232 protocol was chosen because it is noise tolerant and ubiquitous.

C. Actuator Control

The actuator board controls the solenoids necessary for all of the pneumatic manipulators on the sub. This year, it controls the servo used to turn the steering wheel, which is a part of the driving task. It also provides power to the kill switch board and sends information from the kill/mission switches, current sense, and the fuse status to the computer. It accepts commands to switch ON/OFF the solenoids and to turn the servos through communications with the computer using an isolated serial line.

D. Thruster Control

The thruster board drives up to eight brushed thrusters on the vehicle. They are powered through custom H-bridge configurations, and their speed is set by the computer over serial lines. Power for the thrusters comes directly from the merge board. The thruster board contains protective fuses, the status of which are reported to the computer. It also receives the kill signal from the actuator board, and uses hardware to halt all thrusters.

E. Sensor Interface

The General Purpose Input Output (GPIO) board has multiple ports to read analog and digital inputs from sensors, as well as output analog and digital signals. It is 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. The GPIO board is currently used to read measurements from the depth sensor, and to measure the internal pressure of the vehicle. It also features a pair of LEDs that indicate the pressure inside the upper hull, to make sure the partial vacuum that is pulled is sufficient.

V. Sensors

Ragnarök’s sensor suite includes two main classes of sensors, one to observe the vehicle’s environment, and one to observe the vehicle’s state. The sensors used to observe the course in TRANSDEC consist of three cameras and a passive acoustic array. There is also a suite of sensors to measure the vehicle’s state, including inertial measurement units (IMUs), compasses, and a Doppler velocity log (DVL).

A. Cameras

Ragnarök uses three color cameras for visual recognition and navigation tasks. The Guppy F-080C and F-046C color CCD cameras are provided by Allied Vision Technologies. The forward cameras utilize fixed focal length, wide-angle lenses from Theia Technologies, while
the downward camera uses a fixed focal length lens from Fujinon (see Figure 11).

![Fig. 11: Ragnarök’s three cameras](image)

B. Doppler Velocity Log

The Teledyne RDI Explorer Doppler velocity log (DVL) provides accurate velocity data on the surge and sway axes. This information is used in conjunction with the other sensors to provide closed-loop velocity control, as well as accurate position data.

C. Orientation

A combination of IMUs and compasses measure the vehicle’s acceleration, velocity, and spatial orientation. The orientation sensors on the vehicle are a MicroStrain 3DM-GX1, a Sparton GEDC-6, a PNI Trax AHRS module, and a team-designed IMU. The custom-built IMU was developed for a fraction of the cost of the COTS sensors. An MSI Ultra-stable 300 pressure sensor measures the depth of the vehicle.

D. Hydrophone Array

The hydrophone system is used to detect the heading and elevation of a pinger relative to the vehicle. The hydrophones include an array which consists of four Reson piezoelectric elements. A combination of analog filtering and digital signal processing is used to process the element data. An Analog Devices SHARC 21369 is used to handle the digital signal processing. Both heading and elevation to the pinger can be measured to within one degree.

VI. Software

All of Ragnarök’s higher level functionality, including completing mission tasks, is achieved through the vehicle’s software system. The software stack is built upon the Debian GNU/Linux operating system and includes custom shared memory, serial daemon, multi-threaded vision, control, and mission systems. All custom software is written in C/C++ and Python.

![Fig. 12: Ragnarök’s software stack](image)

A. Computer

The software on the vehicle is powered by an Intel Core i7-3610QE quad core processor on an mini-ITX motherboard along with an Intel X25-E Extreme 32GB solid state drive (SSD). The computer is connected to dockside through a 100Mbps Ethernet tether.

B. Shared Memory

The shared memory system provides a centralized interface for communicating the state of the vehicle between all running processes, all of the electronics, and all the users controlling the vehicle. It is a custom system built upon POSIX shared memory, providing thread- and process-safe variable updating and notification. It is responsible for storing the vehicle’s state.
in a number of type-aware variables. These shared variables can be accessed by all of the components of the software system, which allows for simple communication among the various daemons.

C. Unified Serial Daemon

The Unified Serial Daemon (USD) handles communication between Ragnarök’s on-board computer and the internal electrical boards by implementing a standardized serial protocol. With the USD, a single configurable daemon on the computer is able to communicate with all of Ragnarök’s custom serial-connected boards. A variety of functionality is built into the USD protocol, such as board identification, and microcontroller monitoring.

D. Vision

Our vision-processing system is designed to give the vehicle up-to-date and accurate data about the surrounding mission elements. A vision daemon handles the process of reading and processing camera data. An undistortion filter provides usable data from a wide-angle lens. Processing the vision output is done using a combination of color thresholding, Canny edge detection, and contour and Hu moment analysis. Ragnarök supports two forward-facing cameras which enables a stereovision system to visually determine distances to objects. A third camera provides downward-facing vision for the mission elements located below Ragnarök.

1) Vision Tuning: A vision tuning system enables fast, real-time adjustments to the vision parameters. Since making reliable vision is an iterative process, it is important to have a system to quickly adjust it. The vision tuning user interface shows the results of intermediate steps and makes it easy to see the results of the tuning changes as they are made.

2) Vision Processing: Each mission element has its own vision module which can be started independently of every other module. This lets us save processor time by only running the necessary processes and for multiple modules to be run in parallel. Mission elements are detected by a combination of edge detection, color thresholding, and contour analysis, though not all elements use every algorithm.

3) CAVE: The new CUAUV Automated Vision Evaluator (CAVE) helps analyze vision performance by keeping a database of logged video and providing a graphical framework for quick annotation and automated testing. CAVE organizes captured logs and allows searching by metadata, including information such as the weather conditions within a video, where the video was taken, and which mission elements are present within a video. Additionally, the system can play video files on demand and stream frames directly to the existing vision framework, eliminating the need to manually link log files and videos.
E. Vehicle Logging and Simulation

The logging system captures the full shared-memory of the vehicle during mission runs. Furthermore, a log playback utility was developed which allows the software team to simulate the vehicle with real mission data and to do additional debugging and development out of the water. This system has proven to be extremely useful, freeing up time and reducing software errors. Importantly, this system helps isolate bugs which only occur rarely – for instance, a bug that may occur once in every hundred mission runs. Another utility was built on top of the logging system to give us our mission breakdown by time to allow us to speed up missions.

A 3D vehicle simulator built on the open-source software Panda3D Simulation Engine is used to verify mission and vision code before it is brought to the pool. The simulator can use the same code as used on the vehicle and saves many hours of in-water testing, and provides visual feedback to the software team during development.

F. Mission Planner

The mission planner sits on top of all other software subsystems to control mission execution. It allows a user to run the sophisticated missions required by the AUVSI/ONR AUV competition. The mission planner is built upon two subsystems: a planner and a task subsystem. The planner starts and controls a sequence of tasks, each of which may create subtasks to be run in parallel or in series.

The mission planner is a tree-walking program written in Python that instantiates each element of the user-given task list – allowing the tasks to add sub-tasks – and executes these subtasks in parallel when it is their turn. The planner is always running in the background, ready to cull completed tasks and notify tasks further down the line that it is their turn to run. The planner also makes sure that exclusive tasks (such as movement primitives) only run one-at-a-time and that each task is run at a regular interval.

G. Locator

The locator is an experimental system being run exclusively on the buoy mission elements this year, which can be used to locate targets at a mission-element scale. It creates a top-down two dimensional map of a region of interest and stores, for each point, an estimate of the probabilities of finding the target mission element at that point. As the mission progresses and more data is collected through vision processing and other sensors, the map is updated through a process of Bayesian inference to reflect the increased knowledge of the system. This lets the system gain increasing confidence in the position of the element as it gathers more visual data, improving mission robustness.

H. Mission Layout

The mission layout module creates a map of the course starting with a best-guess estimate of mission element positions taken by human approximation of the course. From there, as the vehicle progresses through the mission, each successfully located mission element is used to further update the map of element positions. As new updates are pulled into the system, the layout of nearby elements is adjusted to accommodate the new information and to provide a better approximate location of the next element. Pipe headings and other directional information can also be incorporated to give good estimates of the locations of far-away elements. This system provides a memory of all the past results, a systematic way to propagate partial course information to as-yet unencountered mission elements, and a simple means to recover from mission failures.

I. Control

Using the collected and filtered vehicle state data, Ragnarök is able to have precise and accurate vehicle control for five degrees of
freedom: surge, sway, heave, yaw and pitch. The vehicle uses a hand-tuned PID controller for each degree of freedom. The control system makes it easy for higher-level code, such as mission, to control the vehicle simply by setting desired values for the velocity, depth, heading, and pitch.

For testing and research use, there are also human-drivable controls using the control helm tool. Control helm provides simple keyboard controls. It also provides easy access to control tuning (when in 'expert mode'). Additionally, a new input method this year allows the use of a 3dconnexion SpaceMouse Pro, a 3D mouse allowing easy control of the vehicle along all of its degrees of freedom.

VII. VEHICLE STATUS AND TESTING

Ragnarök is now in the testing phase. Prior to vehicle assembly, the mechanical systems were thoroughly leak tested, and the electrical systems were bench tested. The first in-water test took place on April 21st. Ragnarök had its first autonomous full-mission run in Teagle Hall on June 28th, and testing has continued since.

Fig. 15: Ragnarök in the water at a pool test.

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Fig. 16: The 2012-2013 CUAUV team with Ragnarök