Cornell University Autonomous Underwater Vehicle: Design and Implementation of the Argo AUV

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***Abstract*—CUAUV Argo is the new 2014-2015 autonomous underwater vehicle (AUV) designed and built by a team of 40 undergraduate students at Cornell University. Completed in a ten month design cycle, the vehicle was fully modeled using CAD software, extensively simulated with ANSYS, and manufactured almost entirely in-house. With 15 years of aggregate research and development to enhance autonomous underwater vehicle technology by CUAUV students, this year's vehicle is a further improvement on all previous designs. Argo presents a stronger, lighter, and more agile platform than ever before.**

Particularly notable new advancements include custom brushless thrusters - two of which are mounted on stepper motor driven vector modules, a full PCB plug-and-play backplane, an upgraded Python-based vision system driving new state-of-the-art cameras, and a refactored mission system allowing for superior task execution control. Argo's sensor suite includes compasses, inertial measurement units (IMUs), a Teledyne RDI Explorer Doppler Velocity Log, a depth sensor, an internal pressure sensor, a hydrophone array, a BlueView high-definition imaging sonar, and both forward and downward-oriented CMOS cameras. Returning features include a dual-cantilevered electronics rack, a vacuum-assisted seal, hot-swappable batteries, pneumatic actuators, and unified serial communications.

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. The competition is designed to challenge student-built AUVs with an obstacle course that simulates real-world AUV missions such as precise mapping of the seafloor and construction of subsea infrastructure. RoboSub competition tasks range from shape and color recognition to torpedo firing and fine manipulation of small objects. Each of these missions must be completed by the vehicle independently (without 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 mechanical, electrical, software and business/public-relations subteams.

II. Design Overview

The 2014-2015 primary vehicle, Argo, is a hovering, littoral-class AUV designed primarily to compete in the RoboSub competition. The design is similar to that of work or observation class remotely operated vehicles (ROVs), primarily targeting space-constrained complex functionality and fine-grained positional control.

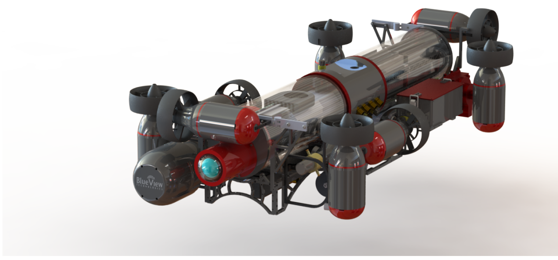

Fig. 1: A SolidWorks rendering of CUAUV's 2015 vehicle, Argo

Argo is an improvement over CUAUV's previous vehicles in terms of fine control, robustness, and ease of assembly. The robustness was improved through more extensive electrical testing, rigorous finite element analysis (FEA), and increased usage of computer numerical control (CNC) machining. Argo features eight thrusters which give it control over six degrees of freedom and improved stability in movement. The vehicle also includes a pneumatic actuator system that allows it to interact with its environment. Argo measures 46 inches in length, 27 inches in width, and 25 inches in height. Its dry weight is 80 pounds.

Custom electronic boards designed by students are isolated in the aft hull and work as interchangeable cards connecting to a central PCB backplane via 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 a single-board computer with a quad-core hyperthreaded Intel i7 CPU, and is primarily composed of intercommunicating shared memory, serial, control, vision, and mission systems.

III. Mechanical Systems

Argo'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 FEA software, and then manufactured either manually or with the help of CNC machinery and computer-aided manufacturing (CAM) software (Pro/TOOLMAKER and FeatureCAM).

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 implements a modular method of component attachement. Waterjet cutting also allowed for rapid manufacture of frame components, allowing for speedy assembly and testing.

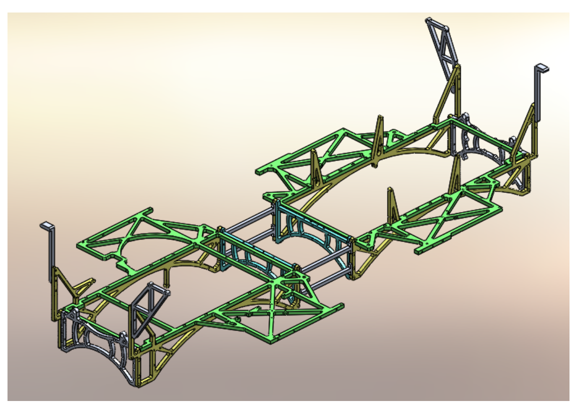

Fig. 2: A SolidWorks rendering of Argo's frame.

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.

B. *Upper Hull and Electronics Rack*

Argo'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 our forward camera, 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, and the rack also raises to a vertical position, allowing for simple and fast maintenance.

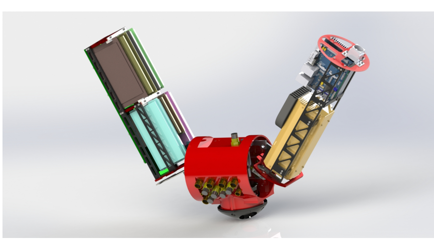

Fig. 3: A SolidWorks rendering of Argo's fore and aft racks.

All connections to the outside of the upper hull are made via SEACON connectors located on the midcap. The midcap provides hinged 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. The fore hull has a camera enclosure built in that slides over the protruding camera. Redundant sealing of the hulls as well as a slight vacuum within the upper hulls renders hull leak risk negligible.

C. *Actuators*

The actuators system is comprised of two torpedo launchers, two marker droppers, two active grabbers, 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. Twelve internal and two external valves, the former housed inside an integrated manifold and valve enclosure, pass air from the valves to the rest of the pneumatic actuators system. With this configuration, Argo can independently fire individual torpedoes and markers, actively grab and release two objects simultaneously, and effectively manipulate forward elements.

1) 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.

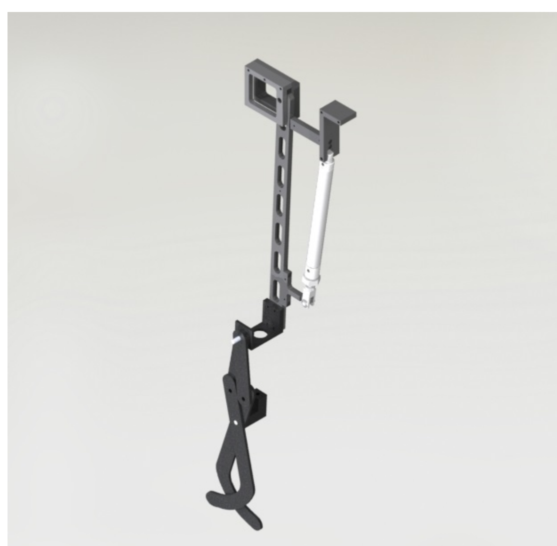

Fig. 4: One of Argo's downward grabbers

2) Active Grabbers: Two active grabbers are responsible for grabbing the recovery objects. Each grabber consists of a pneumatic linear cylinder connected to a claw on an actuated extending arm. The cylinders are double-action; firing one valve closes the claw and firing the other opens it.

3) Forward Manipulator: Argo features a passive forward manipulator utilized to remove ”lids” on mission elements. An X-shaped contact element serves to automatically guide the handle of the lid into the sub’s grasp.

4) Thrusters: Propulsion is provided by eight custom-machined brushless thrusters. Each thruster has a built-in control board allowing for position-independent hot swapping. The two aft thrusters are mounted on stepper-controlled mounts, enabling dynamically directed thrust vectoring. Argo’s thruster mounting scheme provides the vehicle with active control in all six degrees of freedom.

D. External Enclosures

Argo’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 passive acoustic system, kill switch, sensor boom, downward camera, and battery pods.

1) 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.

2) 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 custom team designed compass and IMU. Signals are passed back to the upper hull via SEACON connectors.

3) Battery Pods: 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 outgassing. The battery pod lids are latched to the hull for quick battery removal and replacement.

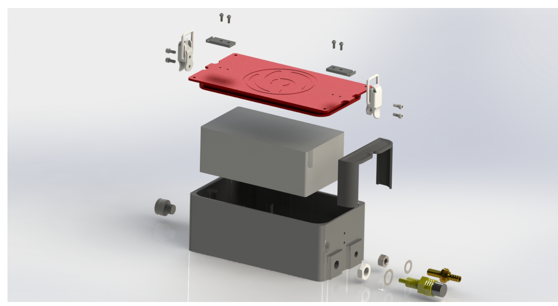

Fig. 5: Argo’s battery pod enclosure

IV. Electrical Systems

Argo’s electrical systems supply up to two hours of reliable power throughout the vehicle and provide an interface between the onboard computer and all sensors and peripheral devices. The electrical subteam designs 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 backplane usage, electrical connections are optimized between boards inside the hull, external enclosures, and sensors exterior to the upper hull. The amount of time required to maintain the electrical system is decidedly reduced relative to previous designs.

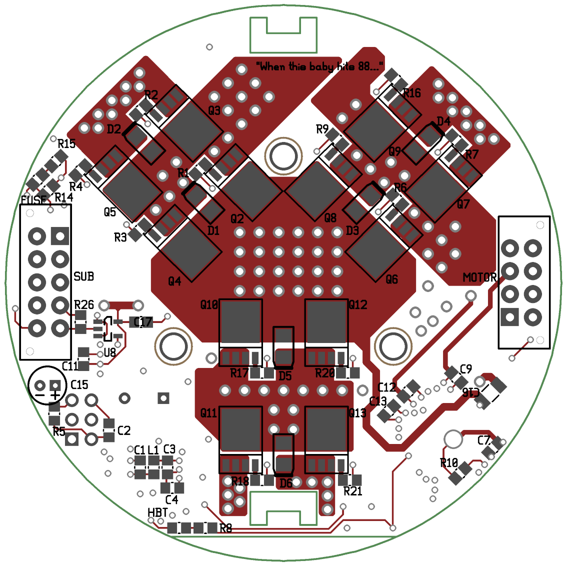

Fig. 6: Layout schematic of Argo's brushless motor control board

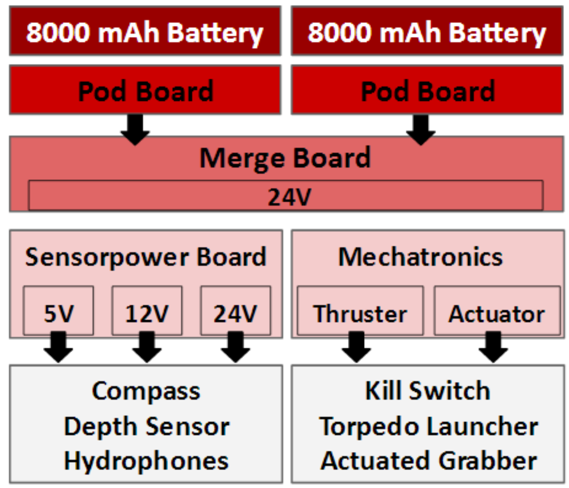

Fig. 7: Block diagram of Argo's power infrastructure

A. *Power System*

The power to run Argo is provided by two Advance Energy 8000 mAh lithium polymer batteries, which give the vehicle a run time of approximately two hours. In order to maintain constant uptime while testing, Argo 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 sourced from the two batteries is routed through the pod 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 pod 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, and +24 Volts. The board measures power use from each port 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.

B. *Serial Communication*

The serial board is the interface between the computer and the various sensors and custom-designed boards. It allows twelve devices to communicate via RS-232 serial through a single USB connection. The RS-232 protocol was chosen because of noise tolerance and ease of use and deployment.

C. *CAN Bus*

The CAN protocol is used to communicate with each of the eight thruster modules as well as the two 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 of the thrusters and 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 thruster control.

D. *Thruster Control*

Each of the eight thrusters contains a custom brushless motor control board. Each board contains a microcontroller to communicate with the computer and control the motor. To abide by safety regulations, all thruster modules, vector thrust modules and the actuator board can be halted either by hardware switch or software.

E. Vectorized Thruster Control

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

F. Actuator Control

The actuator board control the solenoids necessary for all of the pneumatic manipulators on the sub. The actuator board also 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.

G. 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.

V. SENSORS

In order to autonomously navigate through the competition course, the vehicle is equipped with two main classes of sensors: sensors to observe the vehicle's external environment, and sensors to determine the vehicle's internal state. Visual recognition and navigation tasks in TRANSDEC are successfully identified using one forward and one downward camera, while the recovery task is 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), and a high-definition imaging sonar.

A. Hydrophone Array

Argo'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.

B. 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-GX4-25 AHRS and a team-designed compass and IMU. An MSI Ultra-stable 300 pressure sensor measures the depth of the vehicle.

C. 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.

VI. SOFTWARE

All of Argo'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, and abstract task/mission systems. Our custom software is primarily written in C++ and Python, although certain individual subsystems are written in Go and Haskell.

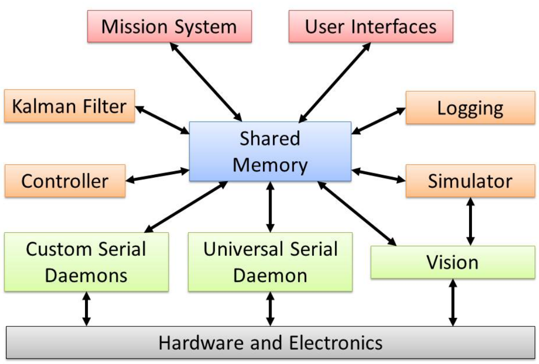

Fig. 8: Argo's software stack

A. Computer

The software on the vehicle is powered by an Intel Core i7-4700 Haswell quad core processor on 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 SEACON Gigabit Ethernet tether.

B. 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.

C. Unified Serial Daemon

The Unified Serial Daemon (USD) handles communication between Argo'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 Argo's custom serial-capable boards. A variety of functionality is built into the USD protocol, such as board identification and microcontroller monitoring.

D. Unscented Kalman Filter

In the past, CUAUV has made use of standard Kalman filtering in order to process the large amounts of raw data from the AUV's extensive sensor suite. Utilizing Bayesian techniques in conjunction with raw sensor data to predict future states of the vehicles position and orientation, Kalman filtering is able to efficiently smooth erratic readings and compensate for any unreliability in sensor data. Although these standard filters have been effective in the past, they perform sub-optimally when filtering nonlinear systems. Because of this, this year's vehicle features an Unscented Kalman filter which processes orientation data, in conjunction with standard Kalman filter for position. By using statistical methods and the Unscented Transform, this new 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 (eg. Gimbal locking). This allows for a much more robust controller and overall enhanced stability for the vehicle.

E. 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. The 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. The undistorted data is then analyzed using a combination of color thresholding, Canny edge detection, contour analysis, and Hu moment characterization among other methods. Argo supports one forward-facing XIMEA xiQ USB3 camera with a wide-angle lens, and a downward-facing IDS-uEye-6230SE-C-HQ Gigabit ethernet camera for the mission elements located below Argo.

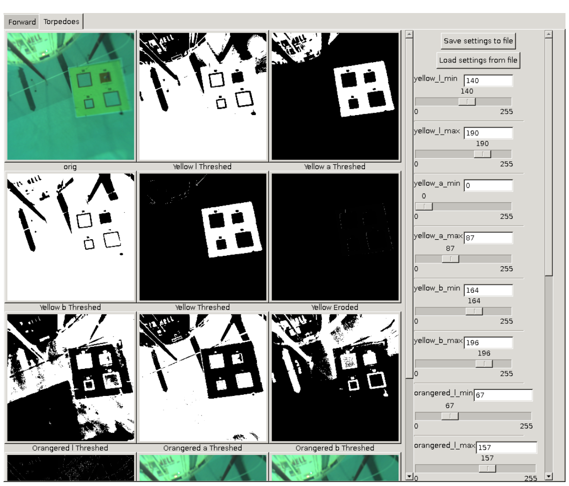

Fig. 9: Vision system graphical user interface

1) 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.

2) CAVE: The CUAUV Automated Vision Evaluator (CAVE) helps analyze vision performance by keeping a database of logged video and providing a graphical framework for quick tag-based annotation and automated testing. CAVE organizes captured logs and allows searching by metadata, including information such as the weather conditions, location, and mission elements present in a video. Additionally, the system can play video files on demand and stream frames directly to the existing vision framework, allowing for effortless testing.

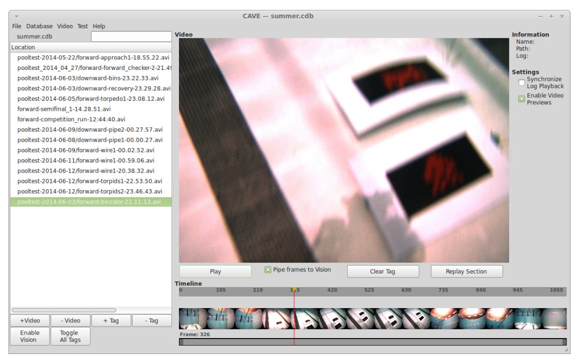

Fig. 10: A screen shot of CAVE running on legacy log data

F. Vehicle Logging and Simulation

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.

We additionally use a fast and extensible networked simulator to rapidly test mission logic. Work to extend the simulator with automated mission unit testing and fuzzing functionality is in progress. The simulator interfaces with our existing shared memory subsystem, so simulated missions can be run without modification.

G. Mission System

A newly revamped mission system 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. In order to construct robust mission tasks resilient to many failure cases, abstract inheritance and simple finite state machines ("searching", "centering", "dropping") are utilized to minimize the time needed to write and debug these additional components.

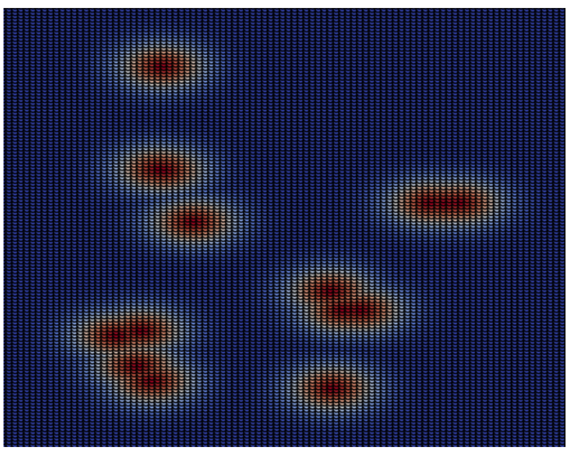

Fig. 11: ASLAM map of mission elements

H. ASLAM

In order to accurately navigate between various unpredictably moving elements during a run, our sub constructs a dynamically generated map of objects within the pool, updating it as the mission proceeds. The ASLAM (adaptive simultaneous localization and mapping) suite, an extension and generalization of our previous locator and layout algorithms, is built on standard Bayesian statistics, using observations of an object to probabilistically predict that object's location. Instead of the covariance model used last year, ASLAM constructs a probability density map for the sub in addition to all the elements, serving to compensate for systematic positional error. ASLAM additionally supports time-based observational weighting, providing an increased level of responsiveness to non-static mission elements.

I. Control

Using continuously collected and filtered vehicle state data, Argo has precise and accurate vehicle control for all six degrees of freedom: surge, sway, heave, yaw, pitch, and roll. The vehicle uses a empirically tuned PID controller for each degree of freedom along with a passive force 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, Argo 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.

VII. Mission Feedback and Diagnostics

Fig. 12: CUAUV's LCD display

Argo features two bipartite ultra bright tri-channel RGB LED strips. The LED strips are powered by a control board which takes input from the vehicle's software via RS-232. These provide visual feedback of the vehicle's current status, which allows for continuous monitoring of mission progress during untethered runs. The LCD display is a new addition to this year's vehicle, and allows for quick and easy reporting of vehicle information without the need for a computer. This is especially useful for system diagnostics, internal pressure monitoring, vehicle trimming display, and thruster testing.

VIII. Vehicle Status and Testing

Argo is 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. Testing is still underway to prepare Argo for the RoboSub competition.

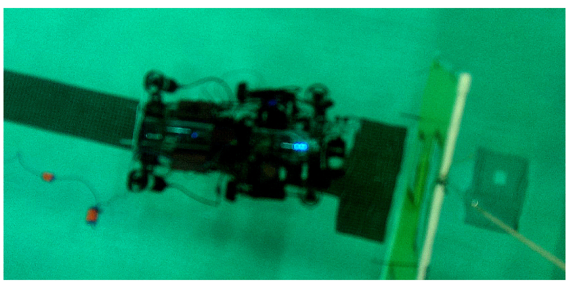

Fig. 13: A pool test of Argo in progress

Acknowledgment

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Fig. 14: The 2014-2015 CUAUV team with Argo