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

Markus Burkardt (leader), Kevin Beaulieu, Corey Chang, Sean Chayanupatkul, Eric Chiang, Brook Du, Kent Esslinger, Zheng Fu, Christopher Goes, Edward Gong, Andrew Halpern, Melissa Hamada, Jeff Heidel, Kylar Henderson, Brendon Jackson, Napon Jatusiripitak, Dong Hyun Kim, Moonyoung Lee, Kevin Lei, Noah Levy, Anne Luo, Mike Mahoney, Alexandru Malcoci, Mihir Marathe, Leo Mehr, Zach Porter, Katie Risvold, Charles Sanderson, Daryl Sew, Kuen-Kuen Sim, Alex Spitzer, Ellen Thiel, Alex Ting, Samuel Tome, Baturay Turkmen, Nancy Wang, Alvin Wijaya, James Wu, Shuqing Wu, Cheng Xing, Rene Zhang, and Mei Zhang.

***Abstract*—CUAUV Gemini is the new 2013-2014 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 AUV technology by CUAUV students, Gemini is the culmination of previous designs. Gemini presents a stronger, lighter, and more agile platform with increased capabilities over previous vehicles. New advancements include full vehicle control of six degrees of freedom, a dual-hull cantilevered electronics rack, overhauled wire routing for electrical systems, and significant software changes which yield improved mission reliability and robustness. Gemini's sensor suite includes machine vision 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 a vacuum-assisted sealing system, hot-swappable battery pods, pneumatic actuators, unified serial communications, and a flexible mission software architecture.**

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 an integral product of many 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 building 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. 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 completing all mission elements and meeting all requirements, the team is divided into Mechanical, Electrical, Software and Business/PR subteams.

II. Design Overview

The 2013-2014 vehicle, Gemini, 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), designed for high functionality and fine-grained positional control. This design was selected to best meet the challenges set forth by the competition.

Fig. 1: A SolidWorks rendering of CUAUV's 2014 vehicle, Gemini

Gemini 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 on the mechanical system. The vehicle was made easier to assemble by strategic placement of the electronics in the upper hull. Gemini features eight thrusters which give it control over six degrees of freedom, improved stability in movement, and a top speed of 1.25 knots. The vehicle also includes a pneumatic actuator system that allows it to interact with its environment. Gemini measures 41 inches in length, 23 inches in width, and 18 inches in height. Its dry weight is 75 pounds.

Custom electronic boards designed by students are isolated to the aft hull, reducing the internal wiring through blind-mate connectors on all the boards inside the vehicle. The vehicle is powered by two lithium-polymer batteries, and contains modular power, sensor, and serial communication systems. A full suite of visual, acoustic, inertial, and pressure sensors is also on-board for use in navigation and data collection. The vehicle's software is run on-board with a quad-core Intel processor, and is built upon shared memory, serial, control, vision, and mission systems.

III. Mechanical Systems

Gemini's mechanical systems consist 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 all sensors, enclosures, and various 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 minimalistic method of tying the vehicle together and allowing new components to be added as necessary in order to overcome unknown obstacles. A T-shaped beam profile is used throughout to maximize rigidity while keeping overall weight low.

Most of the components on the vehicle are screwed directly to the frame, requiring no extra mounting features. This saves weight, reduces complexity, allows for efficient use of space, and makes assembly and disassembly easy. All components are placed such that the center of mass is at the relative center of the AUV, allowing for more stable vehicle control. The frame emphasizes ease of use, manufacturing, and integration while remaining extremely adaptable to the mission.

B. Upper Hull and Electronics Rack

Gemini's reimagined upper hull is composed of two racks, a midcap joining the racks, undersea connectors, the DVL, and two acrylic

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

hull assemblies that protect the electronics. The fore rack contains all commercial off-the-shelf (COTS) components in the upper hull including our two forward cameras, COM Express module, DVL electronics, and LCD display. The aft rack contains all custom electronics linked together and to SEACON connectors via an easily customizable backplane system utilizing Molex Blind Mate Interface (BMI) connectors. All boards slide into connectors via 3D printed rails, and the rack also raises to a vertical position, allowing for simple and fast maintenance.

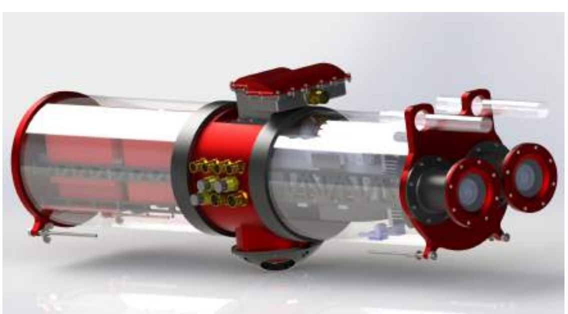

Fig. 3: A SolidWorks rendering of Gemini's upper hull.

All connections to the outside of the upper hull are made via SEACON connectors located on the midcap. The midcap provides mounting for the fore rack, the aft rack hinge, 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 camera enclosures built in that slide over the protruding cameras. Redundant sealing of the hulls as well as a slight vacuum within the upper hulls effectively eliminates the risk of leaks.

C. Actuators

The actuators system is comprised of two torpedo launchers, two marker droppers, up to three active grabbers, and up to two stepper or DC motors. A 3000 psi paintball air tank regulated down to 100 psi serves as the air supply for the pneumatic portion of the system.

Five dual-three-way solenoid valves, housed inside an integrated manifold and valve enclosure, pass air from the valves to the rest of the pneumatic actuators system. With this configuration, Gemini can independently fire individual torpedoes and markers, actively grab and release objects, and 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. 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 Grabbers: Up to three active grabbers are responsible for grabbing the recovery objects. The grabbers consist of a pneumatic linear cylinder connected to a claw. The cylinders are double-action, so firing one valve closes the claw, and firing another opens it.

3) Forward Manipulator: Gemini features an innovative forward manipulator design consisting of a high-traction wheel spun by a high-torque geared DC motor. A funnel helps guide

Fig. 4: CUAUV's peg aquisition and replacement manipulator

pegs to the wheel, allowing for easy removal and replacement of pegs for the forward manipulation task.

4) Thrusters: Propulsion is provided by eight brushed-motor COTS thrusters. Two upgraded SeaBotix BD150 thrusters are used for sway and four for heave due to their symmetrical thrust profiles. The surge thrusters are two VideoRay PRO 3 GTO thrusters, which yield excellent forward thrust. This mounting scheme provides the vehicle with active control in all six degrees of freedom, one more than in past years.

D. External Enclosures

Gemini'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 for ease of removal during testing. The enclosure was designed to be as light as possible, and is constructed entirely out of aluminum to facilitate cooling of the hot electrical components on the board. 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 the thrusters and other high power electrical components. The sensor boom is designed to maintain signal integrity and mounted atop the midcap far from any other noise sources. It contains a LORD MicroStrain 3DM-GX1 AHRS as well as a new 3DM-GX4-25 AHRS, a Sparton GEDC-6, 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 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. Battery pods are engraved with paired names and artwork (i.e. Edison and Tesla, Batman and Robin, and Sam and Frodo) in order to more easily keep track of charge and usage status.

Fig. 5: Two of Gemini's battery pod enclosures

IV. Electrical Systems

The primary purposes of Gemini's electrical system are to supply up to two hours of reliable power throughout the vehicle and also to provide an interface between the onboard computer and all sensors and peripheral devices. The electrical subteam designs custom circuit boards using various schematic and PCB softwares, populating components in-house, and coding the microcontrollers to ensure robust electrical systems for the vehicle. The dual-hull design of the vehicle emphasizes the strategic placement of electronics and wire management by dividing COTS devices from custom electronic boards.

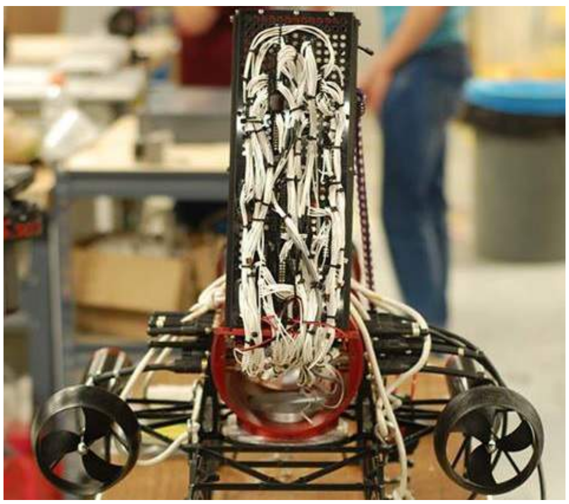

Fig. 6: CUAUV's aft rack backplane, used to optimize electrical connections and route wires.

As a result of this and improved 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.

A. *Power System*

The power to run Gemini 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 a constant up-time while testing, Gemini utilizes hot-swappable batteries, allowing for quick battery changes that do not require a full system reboot. To facilitate extensive use of the vehicle on shore, a bench power station 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, ensuring maximium battery lifetime. 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 provide reliable power rails for sensors, the sensor power board regulates the electrical system with isolated power rails at +5, +12, and +24 Volts sourced from the merge board.

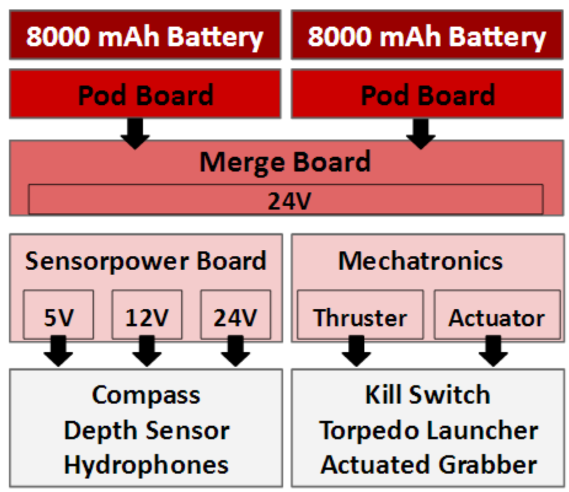

Fig. 7: Block diagram of Gemini's power infrastructure

The sensor power board also 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. The serial board allows fourteen 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. Actuator Control

The actuator boards control the solenoids necessary for all of the pneumatic manipulators on the sub. They also provide power to the kill switch board and send information from the kill/mission switches, and fuse statuses to the computer. The actuator boards also accept commands to switch control the solenoids and to turn the stepper/DC motors through communications with the computer using an isolated serial line.

D. Thruster Control

Each of the two thruster boards control four brushed thrusters on the vehicle. The speed and direction of thrusters are determined through custom H-bridge configurations controlled over serial lines. The thruster board contains protective fuses, the status of which are reported to the computer. To abide by safety regulations, all thrusters and actuators can be halted either by hardware switch or software.

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. In addition to reading measurements from the depth sensor, GPIO monitors internal pressure of the vehicle and reports its status to the computer to ensure the 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: one to observe the vehicle's environment, and one to determine the vehicle's state. Visual recognition and navigation tasks in TRANSDEC are successfully identified using two forward cameras 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, and a Doppler velocity log (DVL).

A. Hydrophone Array

Gemini's hydrophone system uses three Reson TC-4013 piezoelectric elements to detect incoming acoustic waves. With a combination of analog filtering and digital signal processing using an Analog Devices SHARC 21369 to interpret the element data, the hydrophone system accurately calculates the heading and elevation of a pinger relative to the vehicle within one degree.

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-GX1 AHRS, a new 3DM-GX4-25 AHRS, a Sparton GEDC-6, and a team-designed compass and IMU. The custom-built compass and 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.

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 Gemini'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 custom shared memory, serial daemon, multithreaded vision, control, and mission systems. All custom software is written in C/C++ and Python.

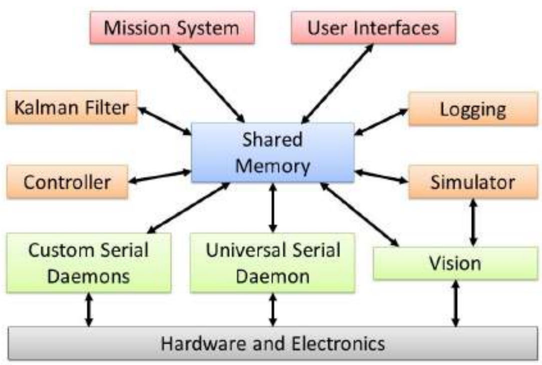

Fig. 8: Gemini's software stack

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 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 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 Gemini'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 Gemini's custom serial-capable 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 reads and processes camera data. Prior to processing, raw camera data is passed through an undistortion filter. The undistorted data are analyzed using a combination of color thresholding, Canny edge detection, contour analysis, and Hu moment characterization. Gemini supports two forward-facing AVT Guppy F-080C cameras with wide-angle lenses which enable a stereovision system to determine distances to objects - a work in progress. A third IDS-uEye-6230SE-C-HQ Gigabit ethernet camera provides downward-facing vision for the mission elements located below Gemini.

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 the tuning changes as they are made, allowing us to rapidly iterate upon our vision analysis algorithms.

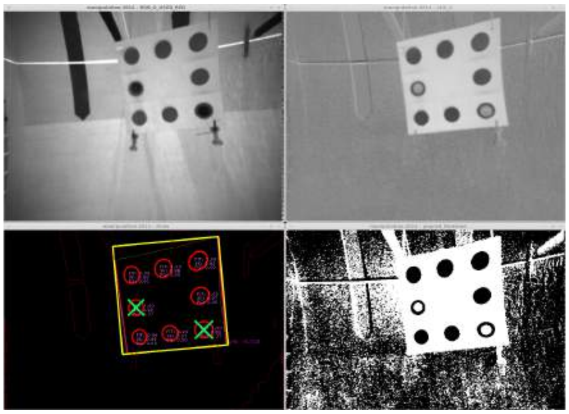

Fig. 9: Manipulation task peg identification

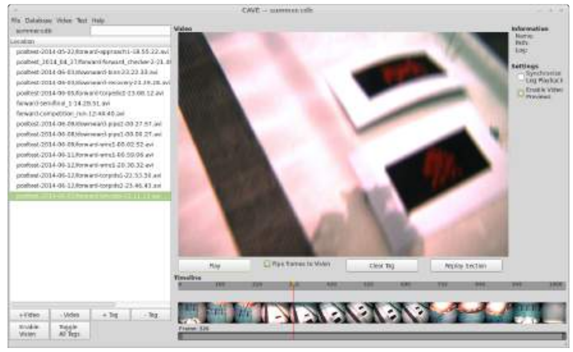

Fig. 10: A screen shot of CAVE

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

3) 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 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.

E. 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. Another utility interfaces with the logging system to give us our task breakdown by time in order to allow mission optimization.

A 3D vehicle simulator built on the open-source 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 the vehicle and saves many hours of in-water testing, providing 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 Gemini to run the sophisticated missions required by the RoboSub competition. The mission planner incorporates two subsystems: the planner itself and a task scheduler. The planner starts and controls a sequence of tasks, each of which may in turn instantiate subtasks.

The mission planner is a tree-walking program written in Python that executes each element of dynamically generated task list. The planner is always running in the background, ready to cull completed tasks and start new ones. The planner also makes sure that exclusive tasks, such as movement primitives, only run sequentially.

G. ASLAM

In order to accurately navigate between various unpredictably moving elements during a run, our sub constructs a dynamically generated

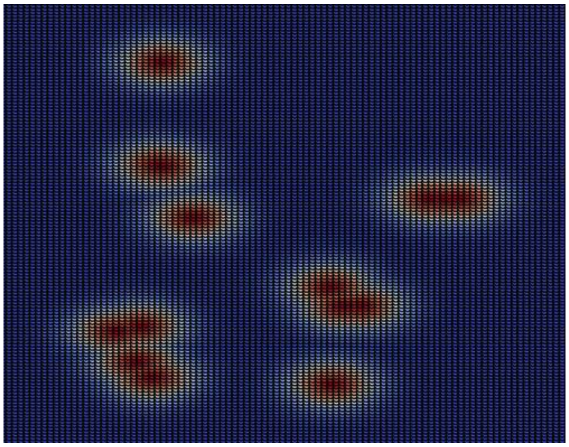

Fig. 11: ASLAM map of mission elements

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 objects 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. Statistically significant heading and distance error measurement and characterization are also incorporated through linear regression. ASLAM supports time-based observational weighting, providing an increased level of responsiveness to non-static mission elements. Finally, in addition to large-scale layout tracking, ASLAM provides generic Bayesian localization algorithms incorporating automatic error rejection in a portable package that can serve both to track elements for which vision data is unreliable and perform generalized triangulation to estimate distance data from heading measurements over varying orthogonal offsets.

H. Control

Using the collected and filtered vehicle state data, Gemini is able to have 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. The moment of inertia tensor of the vehicle is estimated from CAD to allow for better movement predictions. Using this system, Gemini 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.

For testing and research use, Gemini also provides a manual control helm with simple keyboard input and incorporated control tuning. Alternatively a standard 3D mouse can be used to allow easy control of the vehicle along all of its degrees of freedom.

VII. Mission Feedback and Diagnostics

Fig. 12: CUAUV's LCD display

Gemini features four bright LED strips, as well as a 3.2" LCD display. 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 status, which allows 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

Gemini 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 on March 16th, almost a month earlier than any other CUAUV vehicle's initial test. Testing is still underway to prepare Gemini for the RoboSub competition.

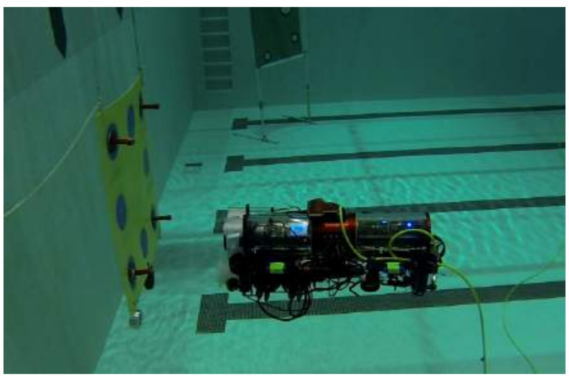

Fig. 13: Gemini in the water at a pool test.

Acknowledgment

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Fig. 14: The 2013-2014 CUAUV team with Gemini