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

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***Abstract*—The CUAUV Killick 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, Killick presents a smaller, lighter, and more agile platform with increased capabilities over previous vehicles. New advancements include a lighter frame and hull, a vacuum-assisted sealing system, an improved electrical system, and significant software changes which yield improved mission reliability and robustness. Killick's sensor suite includes three color cameras, three compasses, three inertial measurement units (IMUs), a Teledyne/RD Instruments Doppler velocity log, a depth sensor, an internal pressure sensor, and a passive hydrophones system. Returning features include the single-hull cantilevered electronics rack, hot-swappable battery pods, pneumatic actuators, unified serial communications, and flexible mission software architecture. Killick weighs 20% less than its predecessor, is smaller in every dimension, and has a significantly longer battery life.**

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. Possible competition elements range from shape and color recognition to torpedo firing, where every task must be completed by the vehicle independent of human control or interaction.

To build 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 2011-2012 vehicle, Killick, 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 ROVs, designed for high functionality and fine-grained positional control. This design was selected to best meet the challenges set forth by the competition.

Killick 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) on the mechanical system. The weight was reduced through the use of FEA, and by relying heavily on

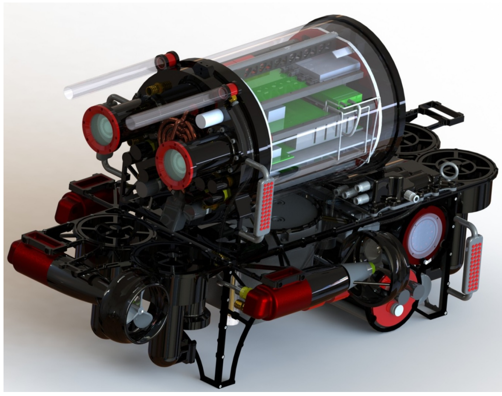

Fig. 1: A SolidWorks rendering of the 2012 vehicle Killick

computer numerical control (CNC) machining to remove all unnecessary material. 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's dry weight is approximately 75 pounds and it measures 31 inches in length, 21 inches in width, and 19 inches in height. Killick 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 it has 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 itself is built upon shared memory, serial, control, vision, and mission systems.

III. Mechanical Systems

Killick'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. The actuators move the vehicle and interact with the vehicle's environment.

A. Frame

The main goal in designing Killick's frame was to significantly reduce its weight while keeping the total part count low. To make the frame easy to assemble, it is constructed from five separate pieces. These pieces were cut from sheets of aluminum using a CNC mill. To make the frame as lightweight as possible, thorough finite element analysis was done in ANSYS to remove any unnecessary material. The frame takes its inspiration from aerospace design (see figure 2).

As a result of this rigorous analysis the frame weighs only 2.42 pounds, an 87% reduction from the previous vehicle's, which weighed 18.42 pounds. Furthermore, the reliance on CNC machining cut the manufacturing time of the frame down from 110 hours to 15 hours. Finally, since it is five total pieces, the frame takes less than thirty minutes to assemble. The frame also includes integrated mount points for the thrusters, battery pods, hydrophones system, pneumatics system, and upper hull.

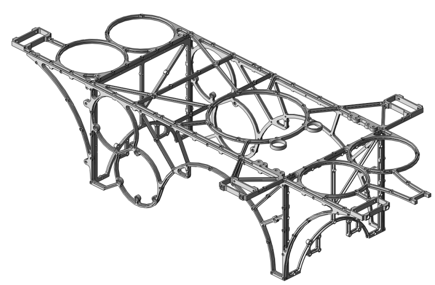

Fig. 2: Killick's frame

B. Upper Hull and Electronics Rack

The upper hull is the main pressure vessel on the vehicle and contains the majority of the electronics (see figure 3). Therefore, it is the most critical sealing component on the vehicle. To assist in sealing this enclosure, a partial vacuum is drawn on the upper hull. The upper hull is sealed with both a bore seal and a face seal, and the vacuum helps improve the effectiveness of the face seal. An additional benefit of the vacuum is that the hull does not require any screws to keep it attached to the vehicle; it simply has two small screws to support the buoyant force on the cantilever.

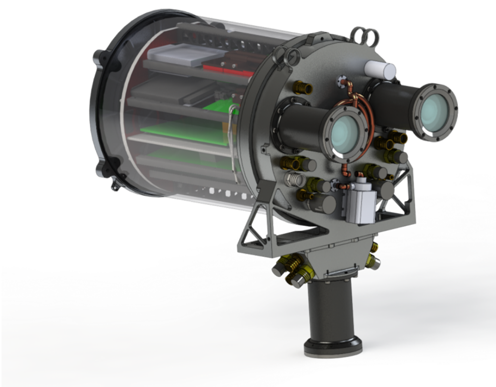

Fig. 3: The upper hull pressure vessel contains most of the Killick's electronics

The hull is an acrylic tube epoxied to a thin rear end cap. This end cap contains a valve which can be easily opened or closed, and is used to draw a partial vacuum in the hull. The other end of the hull is epoxied to a forward sealing collar which seals to the front end cap of the vehicle with both a face seal and bore seal. The front end cap provides a single interface for power and data to pass through the hull.

The front end cap also has mounting points for the three camera enclosures, two forward and one downward. These integrated camera enclosures circumvent the problem of running FireWire cable underwater, which has been problematic in the past. An expansion chamber passes eight SEACON and one FireWire connector to the main electronics rack from below.

The hull surrounds the electronics rack, which consists of a single compartment for boards with cooling fans on the aft end (see figure 4). The fore end of the rack attaches to a bulkhead with blind-mate MicroFit connectors. This backplane is used to interface between the boards and end cap, and makes electrical maintenance of the vehicle much easier compared to previous years. The electrical boards themselves slide into slots on the rack, entering the aft of the vehicle and mating with the connectors on the fore of the rack. This design reduces the amount of wire routing that must be done when adding and removing electrical boards from the vehicle.

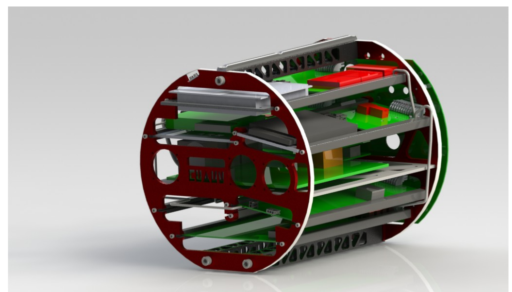

Fig. 4: The electronics rack provides support for the vehicle's custom electrical system

C. Actuators

The actuators system is a pneumatic system comprised of two torpedo launchers, two marker droppers, and an active grabber. A 3000 psi paintball air tank serves as the air supply for the entire system. The pressure is then regulated to 100 psi by a paintball regulator. This is then passed to eight valves, four on either side of the vehicle. With this configuration, Killick can independently fire both torpedos, both markers, and actively grab and release an object.

1) Torpedo Launcher and Marker Dropper: The torpedoes and markers are custom-designed and cast projectiles designed to travel accurately through the water (see figure 5). The torpedoes are propelled pneumatically and have a range of approximately 15 feet.

The markers are also fired pneumatically. They are held in place by magnets and a small air burst unseats them. The markers then fall, guided by large fins and heavy tips.

Fig. 5: A torpedo and marker as used on Killick

2) Active Grabber: The active grabber is responsible for grabbing the recovery object on the course. 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.

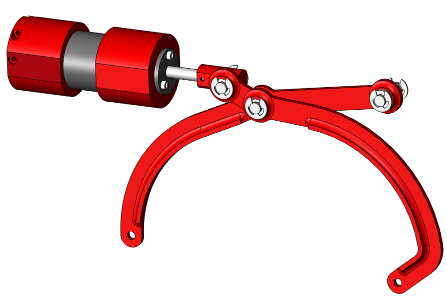

Fig. 6: Killick's active grabber

3) 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 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.

D. External Enclosures

This year an effort was made to reduce the number of separate external enclosures on the vehicle. As such, the only three external enclosures this year are the hydrophones enclosure, the sensor boom, and the battery pods.

1) 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 (see figure 7).

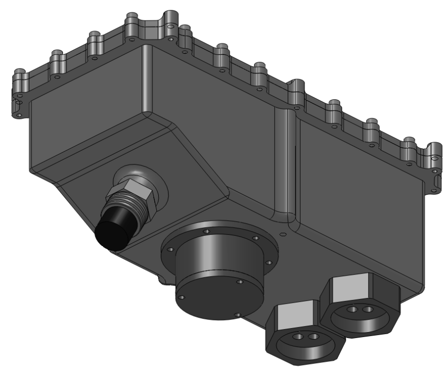

Fig. 7: The enclosure for the hydrophones system

Another mechanical innovation to the hydrophones system this year is the mounting of the piezoelectric elements themselves. Unlike previous systems, the new mounting solution is easily disassembled, and has already been used to test the efficacy of different element arrangements.

2) Sensor Boom: Some of the vehicle's sensors must be isolated from the electromagnetic noise caused by the thrusters. This year, the sensor boom holds the 3DM-GX1 IMU. These sensors are placed in the sensor boom, a plastic enclosure mounted near the top of the vehicle far from any noise sources.

3) Battery Pods: This year's battery pods are enclosures made 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 endcaps. 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.

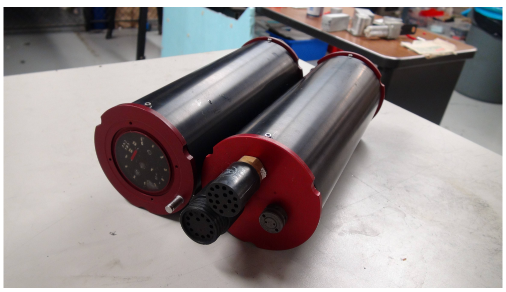

Fig. 8: Killick's new battery pod enclosures

IV. Electrical Systems

Killick'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. Each has a custom-coded microcontroller to interface with the computer.

One of the major changes to the electrical infrastructure this year was the addition of a backplane which the boards blind mate into. 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 Killick is provided by two Thunder Power lithium polymer batteries which give the vehicle a run time of about an hour and forty minutes. 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. Furthermore, a display board indicates the battery charge level when swiped with a magnet to allow for quick inspection of battery status.

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.

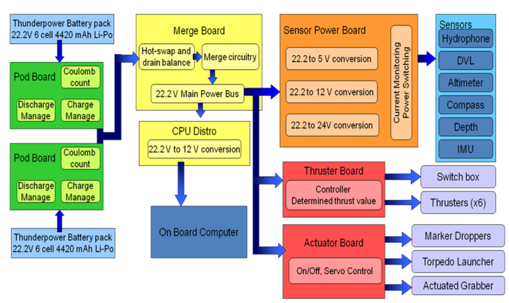

Fig. 9: Block diagram of Killick's power infrastructure

One new development in Killick is the addition of three bright LED strips controlled via the sensor power board (see figure 10). These LEDs are controlled by the computer and are used as visual indicators to the software team of the vehicle's status. This is especially important during untethered runs, as the software team can monitor the mission progress at a glance.

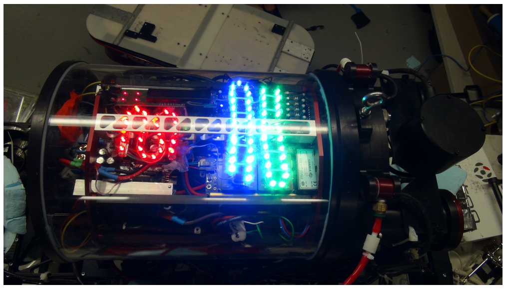

Fig. 10: Killick's LEDs which provide visual feedback to the software team

B. Serial Communication

The serial board is the interface between the computer and the various sensors and custom-designed boards. The serial board allows 14 devices to communicate via RS232 serial through a single USB connection. The RS232 protocol was chosen because it is noise tolerant and ubiquitous.

C. Actuator Control

The actuator board controls the pneumatics system on the vehicle. It provides an interface to allow the computer to fire each of the eight solenoid valves in six different groups for any amount of time. This board also interfaces with the kill switch and mission start button, providing the status of both of these devices to the computer. The kill line going to the actuator board also prevents the valves from firing through hardware if the vehicle is in a killed state.

D. Thruster Control

The thruster board drives the six brushed thrusters on the vehicle. They are powered through custom H-bridge configurations, and their speed is set by the computer. Power for the thrusters comes directly from the batteries since the thrusters are very power-hungry. The thruster board contains protective fuses, the status of which are reported to the computer. The thruster board also receives the kill signal from the actuator board, and uses hardware to kill the motors.

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.

The GPIO board is also used to display data on the vehicle's internal LCD screen. Data such as the pitch and roll of the vehicle, or the status of the batteries can be displayed in real-time on the LCD.

V. Sensors

Killick'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 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) and a Doppler velocity log (DVL).

A. Cameras

Killick uses three color machine-vision 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: Killick's three Machine Vision cameras

B. Doppler Velocity Log

The Teledyne/RD Instruments 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. The DVL also contains a magnetometer, compass, temperature sensor, and altitude sensor.

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 IMU, a Sparton GEDC-6 Gyro-Enhanced Digital Compass, and a team-designed IMU. The custom-built IMU was developed for a fraction of the cost of the COTS sensors, and provides useful data to the CPU. An MSI Ultra-stable 300 pressure sensor measures the depth of the vehicle. Vehicle heading is measured by the internal compass of the DVL, and from the magnetometers in the Sparton compass.

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 higher level functionality, including completing mission tasks, is achieved through the vehicle's software system. The software stack is built on 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.

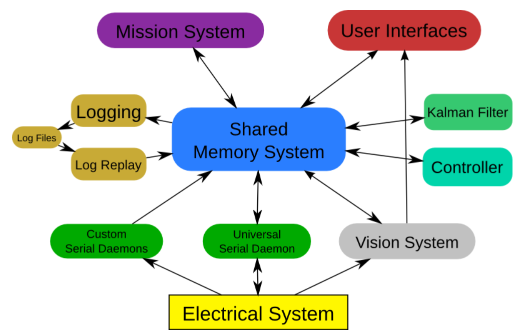

Fig. 12: Killick's software stack

A. Computer

The software on the vehicle is powered by an Intel Core I7-2710QE 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 proprietary 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 the software system, which allows for simple communication among the various daemons.

C. Unified Serial Daemon

The Unified Serial Daemon (USD) handles communication between Killick's onboard 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 serial-connected boards. A variety of functionality is built into the USD protocol, such as board identification, microcontroller monitoring, and the ability to perform logical bit-wise operations on variables. The USD supports board-level access to the shared memory system.

D. Vision Processing

The vision daemon is designed to efficiently capture images from any cameras attached to the vehicle and then provide these images to the image processing code. This integrated vision daemon uses multiple threads to efficiently capture images from the cameras and defines a framework for multi-threaded image processing code. Image processing modules can be dynamically loaded when needed, saving computing resources. All parts of the program were designed with multi-threading in mind, allowing for near-linear scaling when extra cores are added.

Fig. 13: Color thresholding example (pipe)

Image processing for the individual mission tasks is handled by various vision algorithms provided by OpenCV, an open-source vision processing library. A combination of Sobel edge detection, Canny edge detection, color thresholding, and graph segmentation is performed on each frame captured by the cameras to detect mission elements (see figure 13). Not all algorithms are utilized for every mission element.

One of the most substantial changes to vision processing this year is the addition of adaptive thresholding. This algorithm reduces the effects of illuminant metamerism: the fact that colors change under different lighting conditions. Thus, Killick's vision system is much more robust to different environments, an issue that has caused the team problems in the past.

E. Vehicle Logging and Simulation

This year, the vehicle's logging system was updated. 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 do additional debugging and development out of the water. This system has proven to be extremely useful, freeing up more time while in the water for additional testing and reducing the amount of time it takes to find software bugs. 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 (see figure 14). The simulator can use the same code as used on the vehicle, and has saved many hours of in-water testing, as well as providing visual feedback to the software team during development.

F. Locator

The locator is an experimental system developed this year which can be used to locate targets at a mission-element scale (see figure

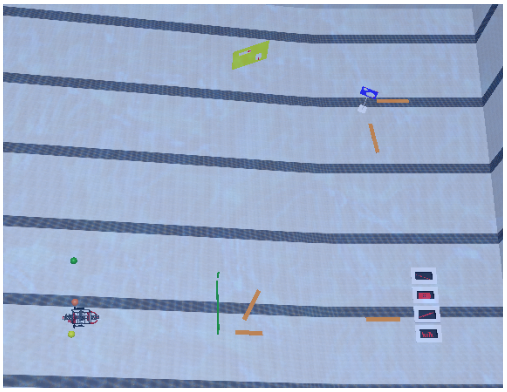

Fig. 14: A screen shot of the Killick simulator.

15). It operates by storing a 2D grid of north-east coordinates and estimating the probability that the target element is in any one location by aggregation of visual and vehicle position data. A probability map of the target element's most likely location is then constructed, which the mission system then uses in order to approach the target. This system allows for successful approaches to targets regardless of imperfect vision data, improving mission robustness.

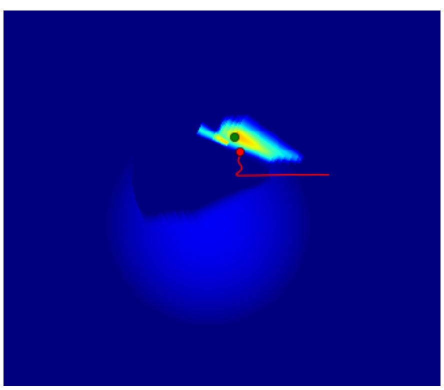

Fig. 15: A typical output of the mission locator. The red dot represents the sub's location, and the green dot represents the most probable location of the green buoy. The colors from blue to red indicate least to highest probability of the green buoy's location.

G. Mission Layout

The mission layout system is an adaptive course mapping utility, used by the mission to navigate the course. It operates by storing an estimate of all element positions within the course which is improved over time with new data using a Kalman filter. The mission layout map starts with a set of pre-programmed position guesses of all the elements. As the mission runs, new pieces of information are obtained, such as a known buoy position or a known pipe heading. This information is then used to update the map and calculate the probable location of the remaining elements. As a result, the mission is capable of navigating the course despite imperfect guesses. Additionally, the mission layout system allows for substantially more reliable recovery in the event of task timeouts, as the vehicle can return to a known location easily.

H. Mission Planner

The mission planner sits on top of all other software subsystems to control mission execution. The mission planner is built upon two subsystems: a planner and a task subsystem. The planner schedules everything from task blocks. This structure allows incredibly rich, dynamic missions to be written quickly, with the planner system taking care of many of the details that would have to encoded in a more procedural system.

The mission planner is a tree-walking, multi-threaded program written in Python that instantiates each element of the user-given task list, allowing the tasks to add sub-tasks and executing these sub-tasks 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 exclusive tasks (such as movement primitives) only run one-at-a-time.

Each task is allowed to give the planner a list of dependencies, which are simply aliases to shared variables. The planner monitors the requested lists of shared variables in separate threads and notifies the tasks to run when their dependencies change. General feedback motion primitive tasks have been developed to abstract the approaching and hovering needed for each element out of mission element specific tasks. This greatly reduces code repetition and allows for the rapid development and tuning of new tasks.

I. *Control*

Vehicle control is achieved using five proportional integral derivative (PID) control loops coupled with a multivariate optimizing layer to handle differing power curves from our six thrusters. By precisely tuning these PID loops, the vehicle is able to hover precisely with minimal oscillation. Data from the vehicle's navigational sensors is fused in a Kalman filter in real time. A combination of velocity, acceleration, angular rate, and orientation is input to this filter, allowing the vehicle to estimate its position and motion regardless of the varied sensor update rates.

VII. Vehicle Status and Testing

Killick 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 May 6th, the first fully autonomous run was on June 19th, and testing has continued since.

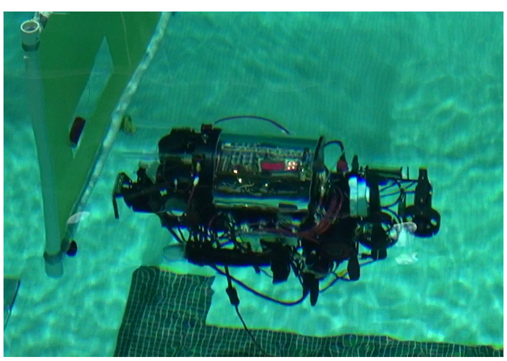

Fig. 16: Killick in the water at a pool test.

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Bronze: Georgia Case; Bittele Electronics Inc.; Turner Construction; Digi-Key; Molex; Polyform; Patriot Memory; Thunder Power RC; Edmund Optics; APC International Ltd.; Keithley; Blue Echnix; Deep Sea Power & Light; Cortland Cable; Polymer Plastics Corporation (PPC); Cayuga Xpress; Ocean Server Technology; First Call Paintball; and Surface Finish Technologies.

Fig. 17: The 2011-2012 CUAUV team with Killick