Cornell Seamonkey AUV

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Abstract— **The Seamonkey, an Autonomous Underwater Vehicle (AUV), was designed and built by the Cornell University AUV team (CUAUV) to compete in AUVSI's annual AUV competition. The 2006 Seamonkey represents an evolution from CUAUV's 2005 design, yielding a more reliable and less complex vehicle. Features which have been successful in the past, such as its dual hull construction, brushless motors, and flexible software configuration have been retained. Problematic components, such as the microcontroller driven Ethernet sensor network within the vehicle, have been removed. Notable improvements in the 2006 Seamonkey include new control and vision systems, better signal integrity, a fiber-optic tether, and USB video cameras. These changes have resulted in a vehicle which is more robust and better suited to the AUVSI competition than its predecessor.**

I. INTRODUCTION

The 2006 Seamonkey design draws heavily from the 2005 CUAUV design. Much of the design philosophy regarding modularity, ease of maintenance and flexiblity of use has persisted. This year we have made major improvements towards reliability, learning to tread the line between flexibility in design and reliability in implementation. Though the overall vehicle favors a flexible approach, particular implementations have been restricted in order to make the overall system more stable. The vehicle has been better geared towards the competition.

II. THE MISSION

The 2006 AUVSI competition will take place in San Diego, at SPAWARs Transdec facility (Fig 1). This year's mission is an evolution of last years challenge, increasing the demand on the vision processing and decision making algorithms. The AUVs goal is to complete a unique operation at each of three stations. A combination of visual and acoustic sensors is needed for the sub to successfully navigate the course.

Mission runs begin at the launching area, with the entire course encompassing three separate stations.

- Deployment: The vehicle must first navigate through an underwater gate to demonstrate its control autonomy.
- Station A: Docking Station. The docking station consists of a clear tube fixed to the bottom of the pool. Inside, a light blinks at a specified frequency. Using visual sensors, the sub must "dock" with the tube by tipping it over.
- Station B: Pipeline Inspection. A series of rectangular orange "pipeline sections" lead to a group of four bins. Distinctive orientations of green stripes differentiate the bins. The vehicle must drop a marker into the correct bin as specified by a light array at the launching area.
- Station C: Surface Zone. By homing in on an acoustic pinger, the sub must surface within a specified octagonal area, the "recovery zone".

Surfacing ends the mission. Bonuses are given for speed of completion, as well as for having a lightweight sub. The complete rules can be found at `http://www.auvsi.org/competitions/Rules_Mission_Final_2006.pdf`.

Fig. 1. Aerial Image of Transdec

III. PHYSICAL DESIGN

The Seamonkey is based on CUAUVs traditional twin-hull and aluminum exoskeleton frame. The hulls are filament-wound carbon fiber tubes, sealed on either end by aluminum end caps equipped with redundant o-ring bore seals. The end caps are held in place with two quick-release pins ensuring quick access to the internal racks. The vehicle is designed such that the upper hull is longer and lighter and the lower hull is shorter and heavier. This ensures a substantial distance of separation between the centers of buoyancy and mass, which imparts a large restoring moment opposing any rotational motion in the roll axis. By ensuring a large distance of separation between centers of buoyancy and mass, passive roll stability is imparted on the vehicle, thus eliminating the need for active roll control through thrusters. The upper hull (Section III-A) houses the computing hardware, microcontrollers, inertial sensors, and other mission relevant hardware, while the lower hull (Section III-B) houses the batteries, power management hardware, and thruster drive hardware. By separating the hardware explicitly by functionality, interdependence is decreased, thus allowed equipment in one hull to be changed or replaced without modification to equipment in the other hull. [1] Major mechanical system improvements this year include the construction of a front and back fairing, more robust side thruster mounts, an additional forward facing sensor mounting structure, and a more reliable marker dropper.

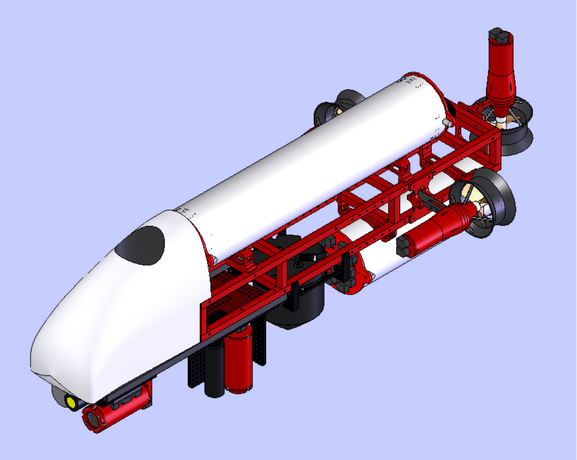

Fig. 2. CAD Model of the Seamonkey

A. Upper Hull

1) Sealing: The upper hull is made watertight by two end-caps, one on the bow side and one on the stern side. The bow side end-cap is removed and reattached every time that the upper hull rack is serviced; as such, it only contains a pressure relief valve to relieve the pressure buildup resultant from the internal air compression caused by reattaching the end cap. During normal operation, the stern side end-cap remains attached to the upper hull. All cables that attach to the upper hull connect through the stern end-cap through one of five SEACON connectors. There are two All-Wet Split Series Pie Connectors, two All-Wet Flat Series connectors, and one Optical Fiber Penetrator. The two "pie" connectors accept the sensor and marker dropper cables, and supports expandability by supplying eight more connector than the minimum. The two flat series connectors accept the lower hull power and signal connection as well as a standard Ethernet tether. Finally, the Optical Fiber Penetrator connects to and supports the vehicles fiber optic tether.

2) Mechanical: The upper hull racks uses a modular mechanical approach consisting of removable rack segments. Segments can be added or removed without the use of tools, enabling rapid reconfiguration and maintenance. The rack currently consists of six and nine-inch long rack segments, although segments of any reasonable length could be integrated in the future. (Any number of segments can be added in any configuration so long as they fit within the length of the hulls inner space.)

B. Lower Hull

The lower hull rack is mechanically divided into two sections: a battery segment and a hardware segment. The battery segment houses the vehicles four Inspired Energy Li-ion battery packs, as well as battery management hardware. (Section V) The hardware segment contains power management equipment, such as a 24V DC-DC, and the thruster motor controllers. (Section IV) This explicit division allows for batteries to be changed out rapidly, as well allowing one segment to be upgraded without affecting the other.

C. Fairings

Front and back fairings were constructed to improve hydrodynamics, provide protection for the sensors in case of a collision, and make the vehicle more aesthetically pleasing. The front fairing was designed with a rounded nose for decreased drag since rounded noses are ideal for subsonic motion. For optimal hydrodynamic performance, the back fairing should be long and vaguely conical in shape. However such a shape is difficult to construct robustly. Instead, the back fairing was also designed as a rounded shape. Carbon fiber cloth was chosen as the reinforcement for its strength and low cost and polymer resin was chosen for its water resistance, adequate strength and low cost. The fairings were constructed by building a positive mold out of shaped Styrofoam covered in automotive body filler as a plug and then layering carbon fiber and resin on its surfaces. To facilitate easy access to the vehicles internal racks, the fairings were designed to be quickly and easily installed and removed from the vehicle using quick-release pins.

With both fairings attached there was a noticeable decrease in the vehicles maximum velocity and yaw rate. It was determined that the open cavity of the back fairing resulted in a high stagnation pressure in the rear of the vehicle and therefore decreased performance. The Seamonkey therefore runs with only a front fairing. The current maximum velocity and yaw rate are similar to those obtained without fairings. However the fairings do produce a marked improvement in the vehicles appearance and provided excellent collision protection.

IV. PROPULSION

A. Thrusters

The propulsion system consists of four custom-designed thrusters which provide the vehicle with active control over four degrees of freedom. Two side thrusters mounted parallel to the hulls provide surge and yaw control, and another pair of thruster mounted vertically perpendicular to the hulls at the front and back of the vehicle provides depth and pitch control. Each thruster is custom designed and built around a Maxon EC-Max 40 70W motor equipped with a 4.3:1 ceramic planetary gearbox and a digital magnetic encoder. After gearing, the output shaft speed is approximately 1,500 RPM. Through the use of the magnetic encoders, the motors can be positioned within 1/500th of a turn; however, the high precision is typically used for extremely smooth low-speed operation. The propellers used are 4.5" diameter, four bladed, bronze propellers.

Fig. 3. Seamonkey's Front Fairing

B. Thruster Mounts

The thruster mounts originally constructed and installed on the Seamonkey were found to be inadequate. With only a moderate amount of force, the thruster mount could be rotated approximately ten degrees in either direction, and driving the motors resulted in an inordinate amount of oscillation. This was found to be due to metal fatigue in the mount, which resulted in plastic deformation and slop in the clearance holes where the thruster mounts attached to the vehicles frame. A milled slot designed for weight reduction was found to be the culprit of the metal fatigue and the slop could be eliminated by replacing the clearance holes with tapped holes. New thruster mounts were constructed with only one slot rather than two, that were half the length of the prior mounts, to further reduce deformation, and the mounting holes were tapped. By shortening the mount, not only were the mounts far stiffer and more stable, but the vehicles extant width was reduced to less than the width of doorways, making the vehicle more easily transportable. Through testing, these mounts were found to rectify the two major problems experienced by their predecessors, displaying very minimal oscillation and slop.

C. Motor Controllers

Four Maxon EPOS 24/5 motor controllers interface with the motor. They are interconnected over a CAN bus, with the head controller connected via a CAN to RS232 gateway to the main computer. Control desires are generated by the control software running on the main computer, which then sends motor values to the motor controllers. The majority of the safety and regulatory measures are handled by the main computer (i.e. acceleration limits in the control software), however the physical “kill switch is the ultimate electrical safety measure.

D. Control and Estimation

Control software on the onboard computer translates abstract desires about movement into desired motor values. The goal for control and estimation was to develop an accurate low-order model in order to implement quadratic optimal model-based controllers for tracking in heading, pitch, and depth. As opposed to pole-placement techniques and proportional-integral-derivative controllers, quadratic optimal controllers provide systematic ways of computing gain matrices [2]. From basic principles, an eight state model was derived that included the following states: heading, pitch, depth, their respective rates of change, speed (measured in the body-axis), and roll. A nonlinear multiple-input (the four thrusters) multiple-output model was derived from basic principles. The model was fine tuned by using least squares techniques as well as by recursive parameter estimation. The vehicle's nonlinear model requires a nonlinear estimator to optimally reconstruct the vehicle's state from noisy sensor measurements sampled at 10 Hz. Sensor noise included biased noise from the thrusters perturbing the heading measurements. For estimation accuracy and numerical stability, a square-root version of the Sigma-Point Filter (SPF) [3] was implemented instead of the Extended Kalman Filter (EKF) [4]. Another advantage of the SPF over the EKF is that linearization is not required around different operating points. The control architecture is composed of two layers: at the lower level Linear Quadratic Regular (LQR) [5] controllers guarantee reference tracking and disturbance rejection, while at the upper level a model predictive control type formulation [6] is used to compute semi-optimal trajectories between operating points and for LQR controller selection.

V. POWER INFRASTRUCTURE

A. Batteries

Seamonkey is powered by a set of four Inspired-Energy SmartBattery packs. Each pack is composed of twelve lithium-ion cells (four series, three parallel) with a nominal voltage of 14.4V. With each fully charged pack providing 95Wh, the full four pack set provides 380Wh of total energy. Under normal operating conditions, the submarine can run for more than an hour on a full charge. Because the packs conform to the SmartBattery specification, they are capable of monitoring their condition and protecting themselves. Therefore, they require only minimal supervision.

Each set of packs is mounted within a special rack segment, creating individual battery modules. Each module can connect to the motor controller segment, together forming the lower hull rack. Since all battery modules are interchangeable, replacement of the batteries is quick and easy.

B. Routing

Each segment of the upper hull rack has its own power distribution board. These boards are responsible for routing the necessary power to the various components both inside and outside the submarine. Raw battery power enters the upper hull rack via the blind-mate and is connected directly to the power board in the rear segment. The power boards in the

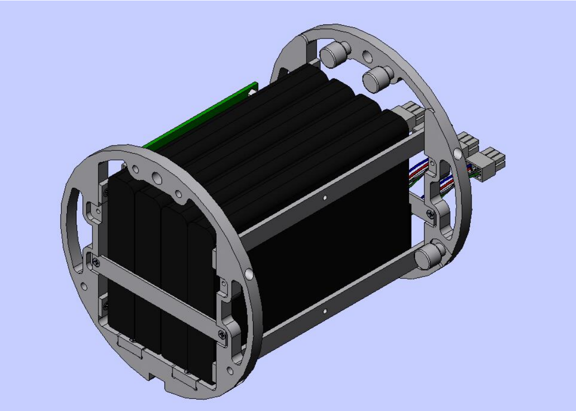

Fig. 4. Battery Segment

remaining two segments are then daisy-chained off that first one. Each board provides four power connectors.

One significant change from last year’s design is that the new power boards only distribute power at the battery potential rather than V_{batt} and $+5V$. Due to the wide variety of voltage requirements throughout the submarine, it was decided that the easiest course of action was to insert DC-DC’s and voltage regulators where necessary. Only running V_{batt} also has the advantage that voltage drops on the main power bus will likely not result in any component browning out.

The power boards also have the ability to measure the current to each of the four power output connectors. Integrated temperature sensors also allow the power boards to monitor ambient temperature of the hull. Current and temperature data is then reported back to the main computer via an RS-232 serial line.

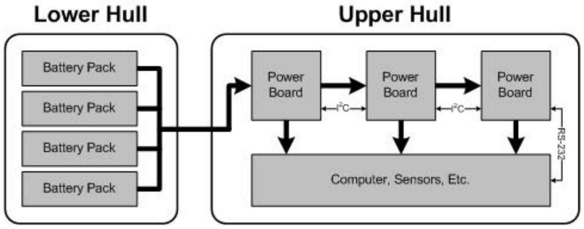

Fig. 5. Power Infrastructure

VI. SIGNAL ARCHITECTURE

Drawing upon lessons from previous designs, the signal architecture of the Seamonkey upper hull rack was modified in order to improve reliability.

The original design called for signal backplane created by a daisy-chaining identical “signal boards using high-density Samtec signal cables. Every signal was broken out on every signal board on a small breakout connector. That design focused upon flexibility, allowing signals to be easily rerouted. However, in order to make the design reconfigurable, many connectors were used. These connectors dramatically increased the number of potential points of failure. [7]

A trade-off was made as flexibility was sacrificed in exchange for reliability. A system of three new boards was built using fewer, more robust connectors. These boards are still daisy chained and a signal backplane is still propagated along the rack. However, each board is now more specialized and reliable.

A. *Breakout Board*

This board most closely resembles the original “signal board. It has two Samtec connectors, serving as a drop-point for signals along the backplane. A significant modification of the breakout board is the addition of a USB-serial connection, effectively allowing up to eight separate serial devices to communicate with the computer.

B. *Signal Board*

This computer interface board routes signals from the onboard computer and the front panel onto the backplane. The signal board is connected to the onboard computer through two 40 pin connectors. One Samtec cable carries VGA, USB and serial from the front panel.

C. *Blindmate Board*

The purpose of the blindmate board is to take the signals from the upper hull to the rest of the vehicle. The blindmate board in actuality is two boards, the rack side and the endcap side. The blindmate board needed only a small amount of improvement to adapt to the new design. The Samtec cable connects directly to the blindmate board instead of passing through unreliable media, as the previous iteration did. This way, the signals stay consolidated and are easily to keep track off.

VII. PAYLOADS

A. *Mounting*

The vehicle has two structures for sensor and external device mounting: the main payload bay and the forward-facing extension.

The main payload bay consists of a series of delrin pieces attached to the frame mounted in a “T” shape with a back. A standard mounting hole pattern is used, so that sensors attached to a generic sensor mount provided by Deep Sea Light & Power can be mounted in practically any orientation downwards, forwards, and sideways. For the competition, the main payload bay will contain the downward facing camera, downward facing altimeter, pressure sensor, and marker dropper.

The forward facing sensor mount consists of a single delrin piece in front of the bow thruster (Figure 6). This new sensor mounting structure was designed with the intent of eliminating certain forward facing sensor problems inherent in the positioning of the main payload bay. By placing sensors in front of the bow thruster, they are provided with an unobstructed field of view and are less susceptible to thruster noise and visual distortions as a result of thruster water flow. For the competition, the forward facing sensor mount will support the forward facing camera, forward facing altimeter, and hydrophone array.

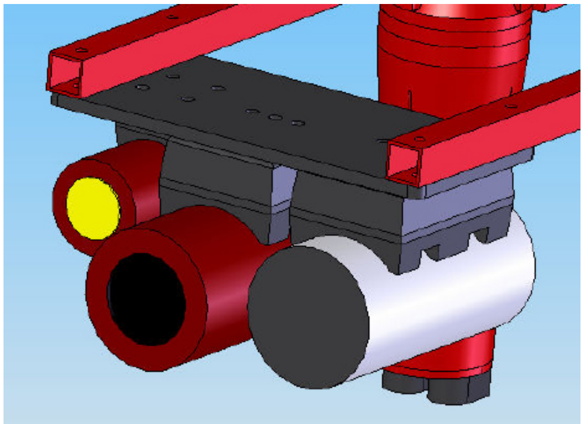

Fig. 6. Forward-facing Sensor Mount

B. Marker Dropper

Significant efforts were made this year to build a more reliable, lighter, and more magnetic sensor friendly marker dropper. Last years marker droppers were designed to be adjustable because only one revision of the dropper could be constructed; this resulted in a lot of additional unnecessary weight. The design relied on a solenoid pulling permanent magnets apart across a piece of aluminum; this proved to be unreliable in that a marker could easily drop inadvertently, or fail to drop at all. The permanent magnets used were fairly strong, and as such, tended to disrupt the operation of the vehicles compasses.

This years marker dropper is designed around the fact that solenoid wire is enameled copper wire, and therefore will not short out when exposed to water. Since both markers were historically dropped simultaneously, the marker dropper was designed to drop two markers at once. The design relies on the markers being equipped with keychain like rings, thereby allowing for a variety of markers to be used so long as they are equipped with a ring. The dropper operates by a solenoid pulling a rod back until the rod is no longer supporting the markers, thereby allowing the markers to drop, and then rubber bands, or another similar tensioning device, return the solenoid and rod to their starting positions once the solenoid is turned off. The mounting plate has slots cut into it, allowing the position of the various elements to be adjusted for optimal reliability. Testing of the marker dropper has been highly successful, with a near one hundred percent repeatability rate once the system has been adjusted properly.

The marker dropper is controlled by a dedicated circuit board that resides in the upper hull. This board is an extensible, three channel power distribution board. The board accepts battery voltage as an input and independently routes it to up to three external devices. The board is controlled by an RS-232 port, which allows the vehicle's onboard computer to control the three outputs. In addition to allowing the computer to turn the loads on and off, the board also supports a timer based command where the board supplies power for a set amount of time and then removes power. This allows the computer to give drop and forget commands to the marker dropper. The board also allows the output status of the relays to be read back by the computer.

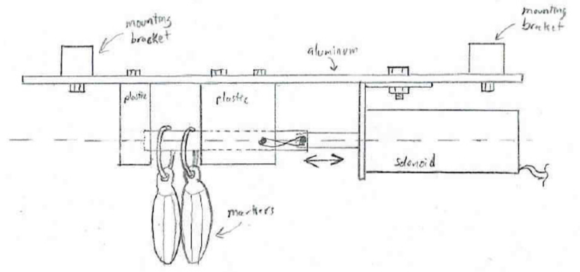

Fig. 7. Marker-dropper Operation

C. Hydrophone

A custom passive acoustic array system was implemented in order to locate the acoustic pinger.

1) Physical Construction: The stand-alone unit consists of an acrylic tube with two o-ring sealed endcaps. One endcap terminates the underwater cable which connects to the upper hull. The other endcap has the sensory array built in.

Four piezo-electric elements with resonant frequency $f_s = 40kHz$ were molded in an alunimium mold using rho-C polyurethane.

2) Analog: A three stage analog filter performs variable gain amplification and filters.

- Instrumentation stage: 10x gain, extremely high input impedance
- Bandpass stage: 10x gain, 1st order bandpass (8kHz, 60kHz cutoffs)
- Variable gain stage: up to 10x gain, high output current

3) Analog to Digital: A high-speed four-channel simultaneously sampling ADC is used to convert the data to digital.

4) Signal processing: Processing is performed using a BlueTechnix core unit which implements an Analog devices Blackfin processor. The PPI interface acquires data from the ADC, the SPI port controls the variable gain, and a serial UART communicates with the mission computer.

Phase data from the four channels are extracted and a heading acquired. Specific navigational decisions are made by the computer depending on the mission code.

D. Naviational Sensors

Other external sensors include a RDI Doppler Velocity Log, two Tritech sonar altimeters, and two USB cameras.

VIII. SOFTWARE INFRASTRUCTURE

CUAUVs Software Architecture is a modular system built around a custom shared memory subsystem. Each of the required subsystems: non-imaging sensor interfaces, control,

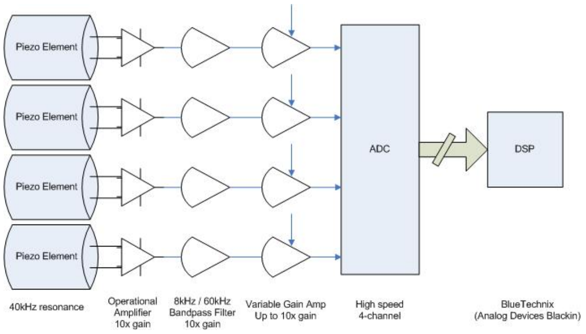

Fig. 8. Hydrophone Analog Amplification and Filtering

vision, logging and mission logic interface with each other through shared memory using the same system first introduced for the 2005 AUVSI competition. This approach easily allows us to swap out individual software modules for development and testing.

The shared memory system provides a fast, efficient, and modular interface between the other subsystems. Originally part the latest implementation of CUAUVs Statecast protocol (detailed in previous years), this subsystem provides fairly simple and easy-to-use C++ and C# interfaces to shared memory, allowing each process to read and/or write multiple "shared variables." Updates are immediately available and large blocks of memory can be effectively shared through Linuxs shared memory RAM disk. Additionally, this module has centralized the flow of information and provided us with a single point at which to log the current state of the vehicle. Finally, the aforementioned Statecast protocol allows the shared memory module of different computers to communicate (albeit at somewhat increased latency), thus giving us the capability to test individual modules on whatever computer is most convenient (a developers laptop, for example).

A. *Sensor*

Our sensor interface subsystem is responsible for interfacing our non-imaging sensors with the remainder of the code. Each sensor has its own capture daemon, which is responsible for reading the sensor data and making it available to the other subsystems; the use of multiple daemons ensures maximum flexibility as the team tests new and varied sensors. The present system was rewritten from last year to improve reliability by interfacing directly with the sensors over RS-232 in order to reduce the possible points of failure.

B. *Control*

The control system uses shared memory to both retrieve current sensor data and to issue new motor commands; this modularity simplifies testing by allowing us to simulation code instead of the sensor interface code, thus speeding the development cycle.

C. *Vision*

Owing to the high bandwidth of the incoming video stream, the vision subsystem interfaces directly with our Logitech camera. Once completed, the results of the image processing are stored in shared memory. Due to bandwidth requirements, the vision system includes its own logging capabilities.

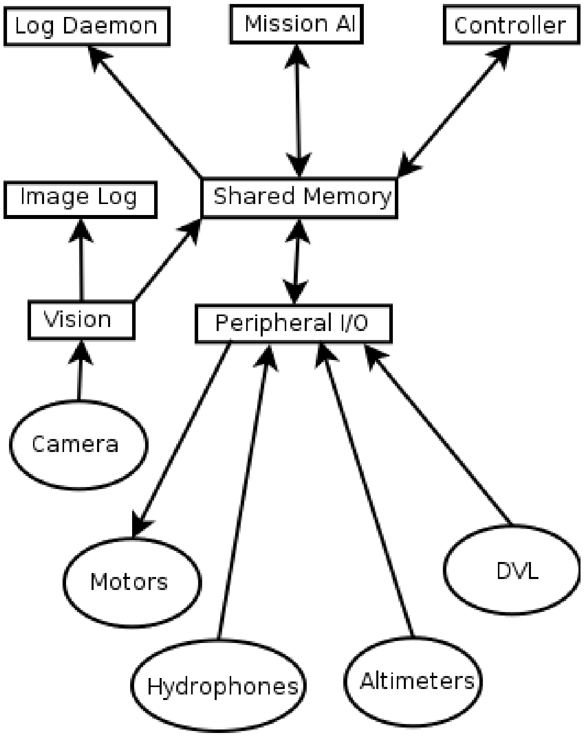

Fig. 9. Software Organization

D. *Mission*

The final and highest-level subsystem is the mission logic subsystem. This module, written in C#, handles all mission-based decision making, goal tracking, and generally helps glue together the functionality of the other software modules.

IX. CONCLUSION

The Seamonkey is a logical evolutionary improvement based on previous Cornell entries. We are confident of the capability of our entry, and look forward to testing its performance in the 2006 AUVSI underwater competition.

X. TEAM MEMBERS

The 2006 CUAUV team is comprised of Adam Hart, Professor Alan Zehnder (Advisor), Alex Acerra, Alexis Collins, Arojit Saha, Bassem Ghali, Ben Evans, Bradley Factor, Brian Decker, Casper Floryan, Professor Charles Seyler (Advisor), Colleen Murphy, Dan Honchariw, Eric Chang, Gopal Parameswaran, Professor Graeme Bailey (Advisor), Gregory Meess, Henry Mason, Ian Wang (Team Leader), Ian Colahan, Jaclyn Klein, James Vaughn, Professor John Belina (Advisor), Kelly Kosco, Professor Kevin Kornegay (Advisor), Liang Ying Chiang, Major Bhadauria, Manoj Lamba, Matthew Pearlstone, Maxim Lobovsky, Morgan Jones, Neil Radia, Paul Otanez, Professor Pedro Perez (Advisor), Sam Fladung, Sana Ahmad, Shahriyar Amini, Shawn Chen, Shawn Liang, Thomas Yen,

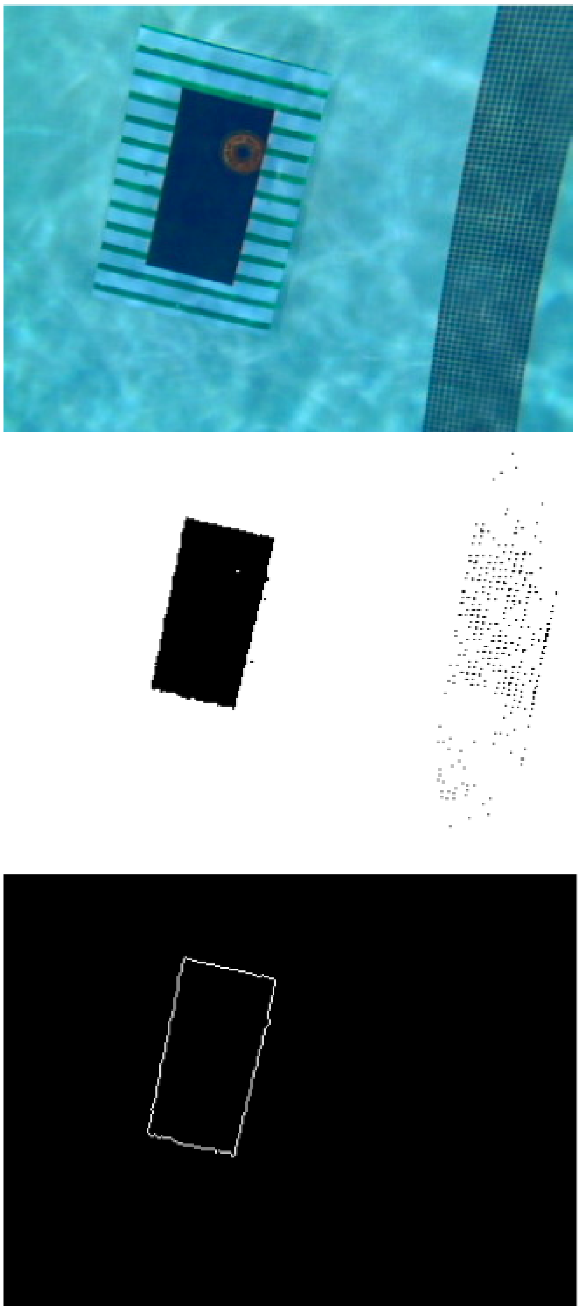

Fig. 10. Vision Algorithm Identifying Bin

Thomas Craig, Wai Siow, William Hui, Yanan Wen, and Yasmin Hovakeemian.

XI. ACKNOWLEDGMENTS

CUAUV would like to thank those who have supported us over the past year. Cornell University, its College of Engineering, the Department of Electrical and Computer Engineering, the Department of Mechanical and Aerospace Engineering, the Department of Computer Science, Cornell Athletics, Cornell Aquatics, and gracious alumni like the Bartels family have once again supplied our team with needed lab space, instrumental tools, and financial aid. Without our corporate sponsors, are ability to compete in the AUVSI competition would be nonexistent. We would like to thank AMD, NexLogic, SeaCon Brantner, Analog Devices, C&C Technologies, Lockheed Martin, Advanced Circuits, DigiKey, ExxonMobil, Keithley, Maxon Motor, Molex, MS-Technology, OceanServer, Samtec, Shell, Tektronix, APC International, Blue Technix, and Mouser Electronics. We would like to thank our long-time advisor Professor Kevin Kornegay who is retiring from that role. We also thank our five new advisors this year: Professor John Belina, Professor Charles Seyler, Professor Graeme Bailey, Professor Alan Zehnder, and Professor Pedro Perez for the contributions they have already made to this team.

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