The SeaBee II: A BeoSub Class AUV

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***Abstract*—The SeaBee II is an autonomous underwater vehicle (AUV) designed and built by students at the University of Southern California to compete in the 10th annual International Autonomous Underwater Vehicle Competition hosted by AUVSI and ONR in July 2007. This years entry is USCR's most ambitious project to date, featuring a powerful, actively water-cooled BeoWulf Class I computing cluster composed of two Intel Core 2 Duo main computers. The design also boasts a brand new lightweight hull, a highly configurable external rack, and a 5 thruster propulsion system allowing easy set up of mission-oriented payloads without the need for constant re-balancing.**

***Index Terms*—Autonomous Underwater Vehicle AUV Saliency Gist Vision Robotics XTX**

I. INTRODUCTION

IN August of 2006, the University of Southern California Competition Robotics Team (USCR) - www.ilab.usc.edu/uscr - began the design process for a brand new autonomous underwater vehicle for the 10th AUVSI competition. This year's competition offers a number of challenges beyond the scope of those of previous years. These new challenges include most notably the addition of a ”treasure” to be recovered from the bottom of the pool. We approached this year's competition with the platform concept centered around the computational workhorse of a Beowulf Class 1 cluster. This platform provides us with a very flexible design that can be tailored to any number of new mission objectives. One of the most challenging aspects of this design was in finding a way to minimize the size of the robot without sacrificing capability. This was acheived through a complete redesign of our hull and mechanical subsystems. We feel that this year's design is the most promising AUV to come out of USCR.

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II. MECHANICAL DESIGN

The mechanical design of the SeaBee II is radically different from its predecessor on many levels. First and foremost, the SeaBee II uses a single hull rather than the compartmentalized design of our AUV last year. In order to arrange all of the components inside of the hull, we designed an internal rack system that is attached to our end-cap, allowing easy removal and thereby granting free access to the entire machine. There is a second rack welded to the outside of the hull which permits not only stable placement of our five thrusters, but also the freedom to place our manipulators and actuators wherever we deem them necessary, allowing for future reuse of the same hull.

A. The Hull

After consulting with the USC College of Letters Arts and Sciences Machine shop, we decided to construct our hull out of machined aluminum 8 inch outer-diameter tube of T6061 aluminum. The design takes inspiration from the deep-sea pressure casings used in oceanographic studies. The tube has a tapered thickness along its length, from 3/8 inch at each end, providing ample room for the o-rings, down to 3/16 inch for the majority of the length of the tube. The result of this tapering is a mass reduction of nearly 40%.

Additionally, the hull has two camera port-holes drilled into it along its underside. These port-holes are machined from separate pieces of aluminum that have been welded into place on the hull. Each block is inch thick and is machined to mount flush to the internal surface of the hull, preventing any constraints on the freedom of movement of our internal rack. Inside each of these port-holes is a block of acrylic that has been machined to fit precisely inside and squeeze the redundant o-rings into place to create a watertight seal.

The front end of the tube is capped with a inch thick piece of acrylic that has double o-rings to seal it in place. This cap acts as a window which allows both for us to see inside during operation as well as allowing our forward facing camera to see what lies in front of the AUV. The back end of the hull is capped with another piece of aluminum that is machined to fit tightly into the hull and provide good o-ring seals. This end-cap acts as the terminal for all of the interaction between the SeaBee II and the external environment. It has been tapped with threaded holes for our Impulse bulkhead connectors, TI pressure sensor as well as two custom machined connectors for our active water cooling system. The cooling system is further detailed at the end of this section while the electronics and sensors are described in the next section.

B. The External Frame

Attached to this hull is a frame of inch square aluminum rods that have been welded into a frame which serves as a mounting platform for our thruster and hard points as well as our marker-dropping actuators, passive manipulators, and our passive sonar array. The frame is designed to support the SeaBee II out of water by turning the AUV upside down, with the cameras facing skyward. This allows us to access the marker-dropping and prevents damage to the manipulators and our sonar array.

C. Thrusters

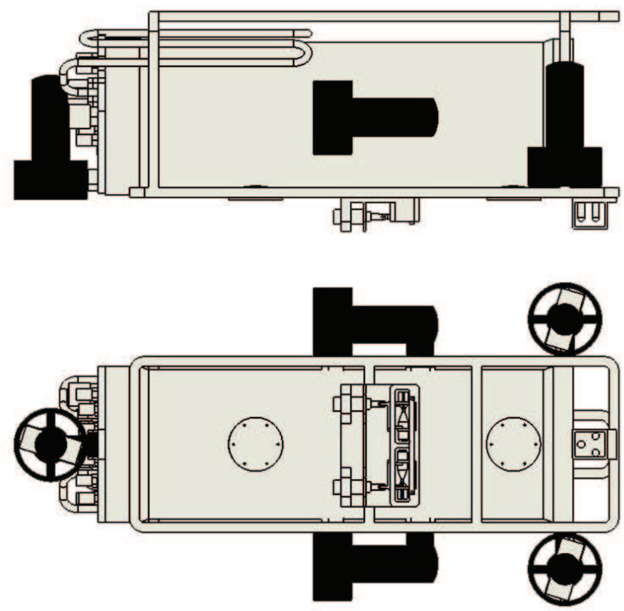


Fig. 1. Thruster of The submarine

We use five SeaBotix BTD150 thrusters for propulsion and depth control. They are arranged in two groups with three thrusters aligned vertically and one pair aligned horizontally. This arrangement allows for fives degrees of control which are used for active balancing through PID control in software to ensure optimal orientation of the SeaBee II. However, we limit the mission specific control to only three degrees of freedom under normal operating conditions. These are rotation about the z-axis, fore and aft acceleration and depth control.

We use three vertical thrusters for active balancing in order to maximize the flexibility of our design. By doing so, we can modify our hull by attaching whatever mission-specific mechanism is necessary without needing to re-balance the SeaBee II for each mission. Using the software control, we can keep the SeaBee II oriented in the proper direction regardless of any shift in the center of mass.

D. The Marker Dropper

The marker dropper was inspired by the bomb bays on B-52 bombers and contains two side by side marker compartments. It is connected to the SeaBee IIs internal electronics via a 4-pin connector on the end-cap. Two of the four pins supply control signals for a pair of water-tight relays mounted on the marker dropper. When these control signals activate the relays, they in turn connect the two solenoids on the marker dropper to a supply voltage which is carried by the third pin on the connector. The fourth pin is the common ground.

Each of the compartments on the marker dropper contains two spring-loaded arms which hold the markers in place. These arms are held in place by a pin mechanism which is attached to the solenoid. When the solenoid is supplied with a voltage, the pins are pulled back, allowing the arms to swing out from underneath the marker. The pin mechanism is also designed to release the arms at slightly different times, preventing them from interfering with one another, and allowing control over which end of the marker starts to fall first.

The markers are highly hydrodynamic and take full advantage of the release mechanism in order to fall in a straight line. The front end of the marker is released first and the end with the fins is freed a split-second later, ensuring that the marker is oriented correctly as it begins to fall. The tail of the marker has angled fins which induce a spin as it descends, ensuring that it falls in a much straighter line than would a spherical marker.

E. *Passive Manipulator*

In order to meet this years added challenge of recovering the “treasure” at the end of the competition course, we have designed a simple arm mechanism which sits underneath the SeaBee II which, coupled with our vision software, allows us to pick up the X shaped treasure and lift it to the surface. The manipulator consists of two outstretched arms which are attached to the external frame of our AUV in such a position as to allow the aft-most camera to judge when the AUV has situated itself in the correct position to lift the treasure.

F. *Passive Sonar Array*

We use three Reson TC4013 Miniature Reference Hydrophones placed in a triangular pattern, in conjunction with a small collection of dedicated electronics to determine the heading from the SeaBee II to an acoustic source. The hydrophones are spaced 2 centimeters apart (center to center) in order to facilitate detection of the phase difference between the signals generated by the pingers. They are mounted to a piece of machined aluminum which is in turn mounted to the underside of the external frame of our AUV. The cables from the hydrophones are also routed back along the hull to the end-cap where they are spliced with SubConn MCIL2M connectors which in turn mate with the corresponding Impulse bulkhead connectors.

G. *Internal Frame*

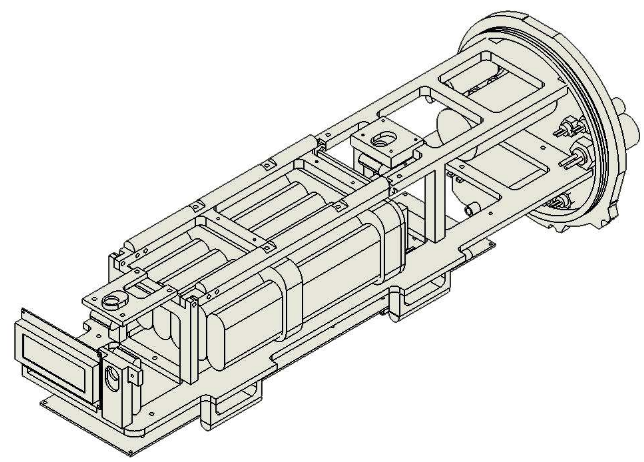


Fig. 2. Internal Frame of the SeaBee

In order to mount all of our electronics inside of the hull, we utilize a custom designed internal frame attached to our end-cap which can slide in and out of the hull on Teflon rails. This frame is machined from aluminum and is designed around our electronics, ensuring a secure mounting platform for every device that is installed in the SeaBee II. We used CAD software to model all of the electronic components and ensure that they would both fit into our hull when it was completed and maximize the efficient use of space within the hull. The rendering above demonstrates the utility of this design.

The 6 battery array is the most bulky of the components and as a result determined the diameter of the hull. This array sits underneath the center rails of the frame and is attached to a separate piece of aluminum which acts like a trap-door to provide easy access to and replacement of our batteries. The primary circuit boards and cooling block are attached to the opposing side of the frame.

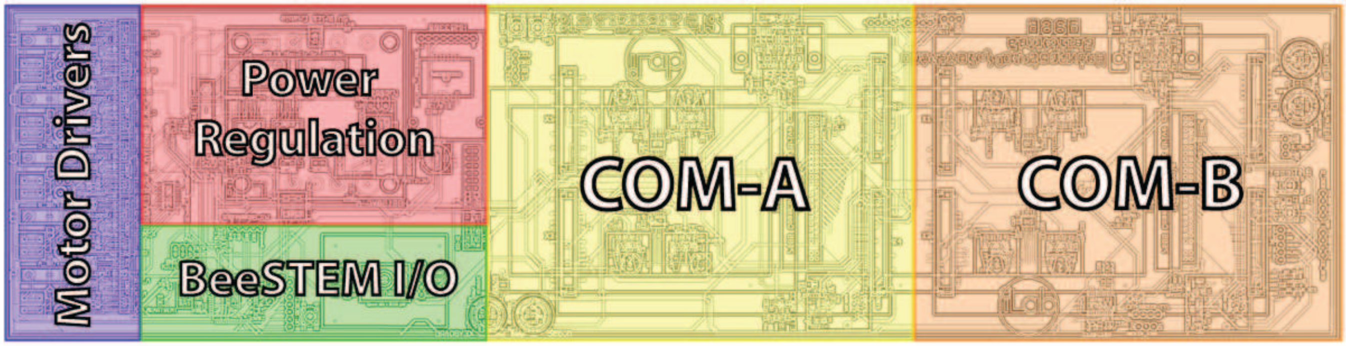


Fig. 3. Main Board Schematic Overview

H. Cooling System

Because the SeaBee II utilizes two Core 2 Duo processors in addition to a series of other heat producing elements, it is necessary to provide a cooling system to prevent thermal damage to the electronics. To that end, we designed a unique water cooling system consisting of two cooling blocks and an external radiator in addition to a pump and reservoir. The primary cooling block is mounted to the standard XTX heat-spreaders to cool our two CPUs while the second smaller cooling block pulls heat away from the motor-driver H-bridges. The radiator is designed to be both light and effective, consisting of a series of copper pipes attached securely to the end-cap and extending just between the hull and the external frame. The radiator is oriented upwards while the AUV is in operation, but rests underneath the electronics when the SeaBee II is on dry land, preventing any missed drops of water from wreaking havoc on the exposed circuit board when the internals are removed from the hull.

III. Electrical Design

Because of our roots in an Artificial Intelligence and Vision laboratory, the SeaBee II's electrical system was designed with the goals of maximizing computing power and maintainability while minimizing cost. To achieve this every electrical component is mounted on, and directly connected via a single printed circuit board (PCB) backplane. The only exception to this is the power regulation board, which is mounted to the battery pack for mechanical reasons. The rest of this section will be divided into discussions of the following subsystems: power regulation and distribution, computing, sensing, and actuation control.

A. Power Regulation

The SeaBee II is powered by 6 Inspired Energy Lithium Ion Batteries arranged into three parallel nodes. Each node consists of two batteries arranged in series, outputting roughly 21 Volts. To ensure equal power draw across each of the three nodes, a small PCB is inset directly onto the tail end of the battery pack that contains all of the mechanical and electrical parts necessary for the interface. On the board, a set of low loss power path controllers is used to measure the output of each node, and switch the node with the highest measured voltage to drive the output via power MOSFETs. An external power connection is also connected to the circuit as if it were a battery node so that the batteries can be shut off and the submarine can be made to run off of external power simply by supplying slightly over 21 Volts. The end result of this is a constant source of power fed from the battery board to the main board without interruption regardless of the individual battery charge levels.

Once on the main board, the raw battery voltage is split up to drive various components. One DC-DC switching regulator efficiently drop the voltage down to 12 Volts for the water cooling pump as well as the marker dropper, while another brick style DC-DC regulator provides 5 Volts for the rest of the electrical components. Because every power regulation component induces power losses, the thrusters use the raw 21 Volts and rely on H-Bridges to drop the power for them using pulse width modulation.

B. Computing

The computing system of the SeaBee II is the true heart of the design. In order to adhere to our single board philosophy, two XTX Computer On Modules are mounted directly to the main board and are able to communicate to every single subsystem via the integrated backplane nearly eliminating the need for wires and cables. These modules, dubbed COM-A and COM-B, are separate 1.66 GHz Intel Core 2 Duo processor computers with only four board-to-board connectors as outputs each in a 3.7 x 4.4 form factor. These 100 pin connectors provide interfaces for every aspect of the boards from power input and output to VGA, USB, and Ethernet and allow us to pick and choose which interfaces we need to save the maximum amount of space. Supporting circuitry, as well as the physical connectors had to be designed and placed directly on the main board alongside the data buses and power planes. The two boards are networked together via an Ethernet switch and together they make up a small Beowulf Class I cluster to evenly share computational loads. Each board also has its own 40 Gigabyte hard drive as well as 1GB of RAM. Such large hard drives were chosen because the incredible amount of on board computing power allows us to use the submarine as our main development workstation. Each computer has 4 USB connectors which provide interfaces for the cameras, and USART buses to provide communication to our I/O chip as well as our passive sonar system.

C. Sensing and Actuation Controller

The SeaBee II has an impressive array of sensors to provide input to the main computers including three high-resolution wide-angle USB cameras, both internal and external pressure sensors, a digital compass with pitch and roll detection, a high speed accelerometer, three internal temperature sensors, a passive SONAR system, as well as current monitors for each of the 5 motors. The three cameras are arranged in a two-down one-forward configuration and are connected directly to the computing cluster via their USB interfaces. The SONAR subsystem is connected directly to the USART of COM-B, and the rest of the sensors are connected directly to a separate I/O processor which connects to COM-B via USART and is described in detail next.

1) BeeSTEM I/O Controller: The majority of the SeaBee II's I/O interfacing as well as actuator control is handled by a 16 MHz Atmel Atmega 128 microcontroller named the BeeSTEM because it acts as a brain stem to the main cluster. The BeeSTEM has two USART ports which are dedicated to communication with the cluster, as well as the HMR3300 digital compass and two dimensional accelerometer. An SPI bus provides communication to the three separate temperature monitors, an LCD display, as well as the high speed accelerometer.

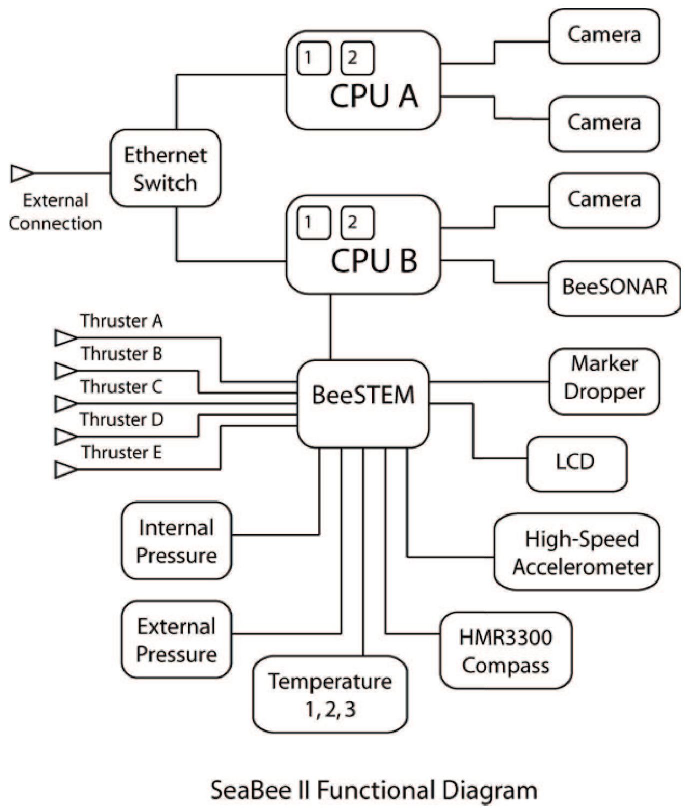


Fig. 4. Functional Diagram of SeaBee II

Additionally, two A/D ports provide readings from the internal and external pressure sensors. All of this information is packaged into a compact protocol and shipped off to the cluster at regular intervals over the USART connection, guaranteeing a regular stream of data. High priority occasional data such as motor current overloads, and internal pressure changes can be configured to be transmitted on a interrupt type basis for regular operation, or as a constant stream for testing purposes. To control the thrusters, the BeeSTEM has five hardware oscillators which run at a software configurable frequency to allow ample room for our passive SONAR system to filter it out. To change thruster speed, the BeeSTEM simply changes a single hardware register used to configure duty cycle. The oscillator is then run completely in hardware, requiring software clock cycles only when changes need to be made.

This feature allows the BeeSTEM to be extremely responsive and able to easily handle PID control based on depth, heading, pitch, and roll readings.

2) Actuation Control: The SeaBee II's thrusters are driven by 5 DMOS full bridge drivers capable of supplying up to 5 amps to each thruster. For safety and power allowance reasons, this current is actively limited by the BeeSTEM through individual current monitors to 3 Amps, the power to each thruster is routed through a 3 Amp fuse to guard against any possible software failures. The motor drivers provide a sense pin to which an extremely low tolerance resistor is connected so that the BeeSTEM can monitor motor current via its onboard analog to digital converters. The only other actuation control needed from the BeeSTEM is the triggering of two solid state relays to provide power for the marker dropper solenoids.

3) Passive Sonar System: The passive sonar system relies on readings from three high quality Reson TC5013 hydrophones situated in a half-phase array at the nose of the submarine. The signals from these hydrophones is amplified and given a DC offset of 2.5 Volts so they can be sampled by a 1.5 MHz parallel analog to digital converter. The sampled data is then passed onto a 80MHz 8-core Parallax Propeller microcontroller. This microcontroller assigns a single core to control the ADC, six cores for data processing, and the last core for data aggregation and communication with the main cluster. The data processing cores each perform a limited bandwidth discrete fourier transform on the data to provide phase and amplitude information for a small set of frequencies. The aggregation core then analyzes the phase shifts and strengths for the designated frequency to determine the exact angle to the frequency source. This angle and strength information is then sent to COM-B via the USART interface.

IV. SOFTWARE

The software system of the SeaBee II is designed with reliability and efficiency in mind. To this end, all the SeaBee II's software is designed to run in a decentralized multi-threaded agent architecture, which is detailed below. To maximize efficiency and speed, the functionality of the submarine is divided up and assigned to run on a specific processor, either COM-A or COM-B, with communication between processes on different processors taking place via an ethernet switch and TCP messages.

A. Vision System

The SeaBee II relies heavily on its vision system for completing the competition's tasks. All of the vision code is written in object-oriented C++ and makes use of the Saliency Neuromorphic Vision Toolkit provided by the iLab at USC as well as the Open Source Computer Vision Library (OpenCV) provided by Intel. Originally, we used our own implementations of various vision algorithms such as the Canny edge detector and Hough transform, but we found OpenCV's implementation of these algorithms to be both more optimized and more extensive than our own and, as such, the SeaBee's vision code now uses the OpenCV toolkit as part of its vision processing system for all of the commonly used vision processing algorithms.

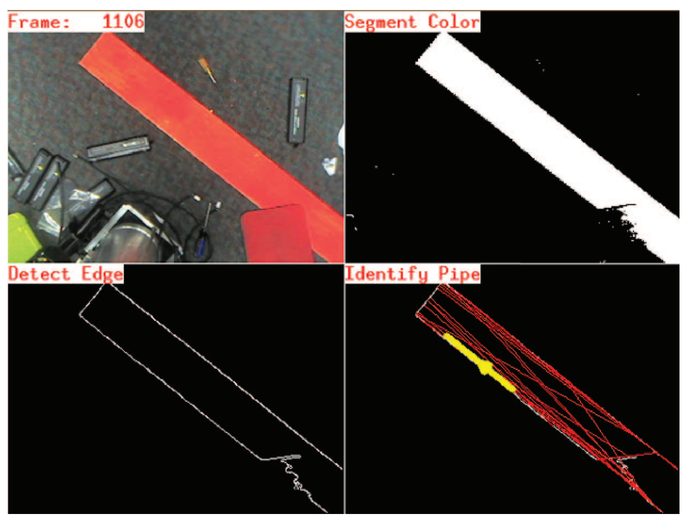


Fig. 5. Pipe Following Algorithm At Work

The SeaBee II's vision system is able to recognize and differentiate between the red flashing buoys in front of the submarine based on the frequency at which each buoy is flashing. Additionally, the system is able to locate and track the orientation of the orange pipeline on the bottom of the pool using a specially tuned type of Hough transform. The vision system is also used to recognize and center over the two bins on the pool floor, as well as detect when the covered bin has been uncovered by knocking the buoy. Finally, the vision system is able to find the X-shaped treasure located over the sonar pinger, determine the center of the X, calculate its orientation, and confirm if our attempts to pick up the X are successful or not based completely on visual cues.

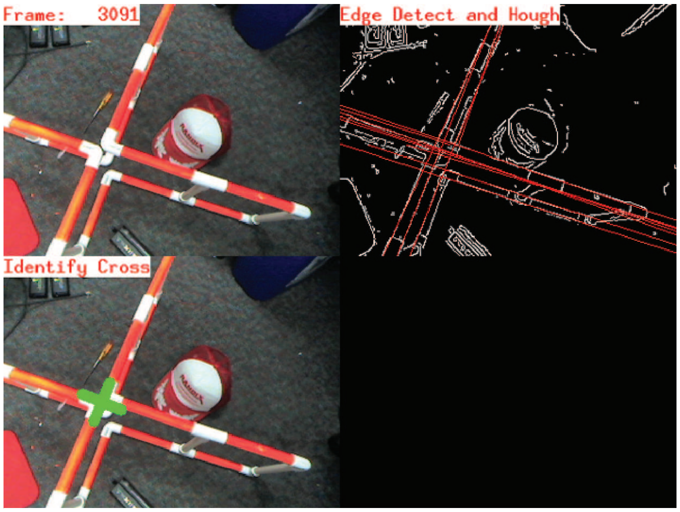


Fig. 6. Cross Centering Algorithm Detecting Center and Angle of Cross

B. High-Level Architecture

The high-level architecture of the SeaBee II makes use of an agent design in the hopes of making a system that is robust, flexible, and adaptive to any unexpected situations that may arise during submarine operation. The decentralized nature of the agent design reduces the risk that the failure of one aspect of the submarine's functionality will cause a failure for the rest of the entire system, while at the same time, allowing for the efficient partitioning of responsibility for various aspects of the SeaBee II's functionality across multiple agents.

1) Agent Design: An agent is a completely autonomous and self-contained entity which has its own logic and set of actions that are separate from other agents. Agents are not capable of controlling the actions of other agents. Rather, agents send messages to each via the Beowulf messaging system and act on the messages they receive in whatever way the logic of that individual agent sees fit. In this way, agents must collaborate with each other in order to achieve the goals of the entire system.

2) Implementation: All of the SeaBee II's functionality from its vision and movement to its mission control is divided up logically and run within an individual agent. There are five agents in total: a Forward Vision agent, a Downward Vision agent, a Captain agent, a Movement agent and a Sonar agent. Each agent is implemented as a BeoWulf thread, allowing effortless portability and seamless communication between them.

The Vision agents are responsible for all of the SeaBee II's vision processing. Vision agents are requested by other agents to look for certain objects around the submarine. If an object is recognized by the Vision agent, the agent which requested that that object be looked for is informed of its location, otherwise, the requesting agent is informed that the object could not be located. The Sonar agent is responsible for locating and tracking the sonar pinger when requested and relaying that information when necessary. The Sonar and Vision agents run within their own individual threads so as to not slow down the operation of other agents when complex vision and acoustic processing occurs.

The Captain agent is responsible for keeping track of the submarine's current mission status as well as deciding what mission objective to go after based on the missions completed as well as the information received by other agents. The Movement agent is responsible for controlling all of the movement of the submarine. When requested by the Captain to complete an objective, the Movement agent makes the appropriate request to the Vision and Sonar agents and moves the submarine based on the information it receives about the location of mission objectives. The Movement agent and Captain agent share a thread.

Fig. 7. Picture of the Complete Submarine

V. Conclusions and Future Work

Thus far, the SeaBee II has proven to be a reliable and powerful platform for AUV research.

We have continuously used the main cluster as our primary development workstation for the past two months and have yet to experience a problem. There are, however, a few improvements that we would like to integrate into future designs, including on-board battery recharging (with precautions taken for the venting of hydrogen), the addition of new high resolution cameras, and we hope to begin developing active sonar techniques for three-dimensional mapping. On the software side, we hope to be able to more fully utilize the cluster's processing power by incorporating stereo vision as well as a full neuromorphic attention-based object recognition system. The goal of our future research is full integration of all our sensor systems to create a highly accurate position and mapping system for AUV localization.

ACKNOWLEDGMENT

The authors would like to thank the Viterbi School of Engineering, as well as all of our sponsors for their continued support of the team. We would also like to thank Don Wiggins from the College of Arts and Letters Machine shop for his incredible work on our hull. Finally, we would like to thank all of the wonderful people at iLab for sharing their space and being always willing to lend a hand.

Randolph Voorhies is a first year Masters Student at USC pursuing his MS degree in Computer Science. He has been on the USCR team since 2005 and took over as president last year. Rand has been instrumental in not only helping to design the printed circuitboards in our sub, but also in creating the BeeStem communications system and programming the microcontroller that controls our primary sensors and actuators.

Chris Roth is entering his fifth year as an undergrad at USC after spending a full year abroad in China prior to joining USCR just before last summer's competition. He will be graduating with a BS in Computer Engineering and Computer Science as well as a BA in East Asian Languages and Cultures. Chris designed the SeaBee's hull and internal mounting system and has worked closely with the machine shop on campus to turn our sub into a reality.

Michael Montalbo is entering his junior year this fall and is pursuing a BS in Computer Engineering and Computer Science. Mike joined USCR in the spring and has been helping design and implement high level control code as well as vision subsystems for the submarine. He has worked diligently with PhD students in Laurent Itti's iLab on the vision software.

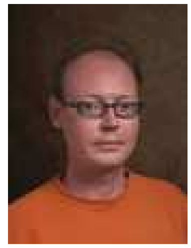
Andre Rosa has been with USCR for the past three years. He graduated in 2005 but he took time off from work to join us at the competition last summer and has helped design and implement many of our vision subsystems.

Andrew Chambers is entering his senior year at USC and is pursuing a BS in Electrical Engineering. He has been involved with USCR in the past, but took over as Hardware Lead for the electrical components of the sub this year.

Kevin Roth is entering his junior year at USC this fall and is also pursuing a BS degree in Electrical Engineering. He joined USCR last fall and has helped design much of the power subsystem in the SeaBee, including designing the voltage regulators on our battery array as well as the H-Bridge motor controlling circuitry.

Neilsen Bernardo is entering his sophomore year this fall at USC as a BS Electrical Engineering major. He joined USCR during freshman year and is primarily involved in the electrical components of the sub. After helping design the schematics for the USB ports, VGA and ethernet of the SeaBee, Neil has been enjoying this really great learning experience.

Christian Siagian is currently working towards a Ph.D. degree in the field of Computer Science. His research interests include robotics and computer vision, such as vision-based mobile robot localization and scene classification, particularly the ones that are biologically-inspired.



Laurent Itti received his M.S. degree in Image Processing from the Ecole Nationale Supérieure des Télécommunications in Paris in 1994, and his Ph.D. in Computation and Neural Systems from Caltech in 2000. He is now an associate professor of Computer Science, Psychology, and Neuroscience at the University of Southern California. Dr. Itti's research interests are in biologically-inspired computational vision, in particular in the domains of visual attention, gist, saliency, and surprise, with technological applications to video compression, target detection, and robotics.