SubjuGator 2007

Kevin Claycomb, Sean Cohen, Jacob Collums, Carlo Francis, Grzegorz Cieslewski, Thomas P. Feeney[1], Donald J. Burnette, Gene Shokes, David Conrad, Hector Martinez III, Eric M. Schwartz, A. Antonio Arroyo

Machine Intelligence Lab (MIL)

(352) 392-6605 www.subjugator.org [1]tom@mil.ufl.edu

ABSTRACT

For the past decade, students from the University of Florida's Machine Intelligence Laboratory (MIL) have brought their minds together to design and create autonomous robots with a focus on solving real-world problems for industry and military applications. Most of the team is currently enrolled in the Electrical and Computer Engineering or Mechanical and Aerospace Engineering departments. These graduate and undergraduate students are continuing the development of the sixth generation of their autonomous underwater vehicle, SubjuGator, after competing in the AUVSI and ONR's 10th International Autonomous Underwater Vehicle Competition. SubjuGator is designed to operate underwater at depths up to 100 feet. A 3.5" Intel Core 2 Duo computer running Microsoft Windows Server 2003 provides the processing power for monitoring and controlling all systems. The mission behavior of SubjuGator is controlled with the Microsoft Robotics Studio framework that communicates with a network of intelligent sensors. The sensor systems include cameras, hydrophones, Doppler Velocity Log (DVL), digital compass, depth sensor, altimeter, and internal environment monitoring sensors. The submarine also makes use of custom-designed motor controllers with current sensing, actuated external devices, and other peripherals necessary for completing the mission. In this paper, we will first describe the construction of the SubjuGator hull and mechanical systems. Next, we will discuss the electronic sensors, custom embedded electronics, and processing hardware. Finally, we will comment on our software implementation, control strategies, and how we would expect a typical competition run to proceed using each of the vehicle's subsystems.

Keywords

Submarine, Autonomous, Robot, AUVSI, SubjuGator.

1. INTRODUCTION

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) sponsored the tenth annual International Autonomous Underwater Vehicle Competition, held in San Diego, California at the SPAWAR facility July 11th through July 15th 2007. A student team at the University of Florida Machine Intelligence Lab developed an autonomous underwater vehicle (AUV) for the 2007 contest. SubjuGator has been completely redesigned to not only meet the new challenges of the competition, but to engage in groundbreaking research projects.

To successfully complete the competition objectives, entrants are asked to complete four tasks. First, the robot will demonstrate autonomous control and orientation by passing through a validation gate. Next, the vehicle will free a flashing start buoy that is anchored to a mooring. After this task is complete, the AUV will track a multiple separated line segments along the bottom to find a target bin. Ideally, the robot will release the second buoy revealing the target bin and drop one marker inside. Finally, the submarine will activate its passive sonar and travel to the appropriate surfacing zone. In this area, the AUV will identify and capture the treasure and surface inside of the recovery zone.

The remaining sections of this paper will focus on how the SubjuGator was created to satisfy these tasks, as well as an in depth look at how each individual subsystem works in tandem with our software to accomplish each specific goal.

2. MECHANICAL PLATFORM

As a sixth-generation vehicle, SubjuGator embodies the lessons learned in the previous nine years of AUV development at the University of Florida. We considered several key design criteria, including survivability in a chlorinated or salt-water environment, inherent stability of the platform while submerged, and future sensor additions.

2.1 Computer Aided Design

To assist in the mechanical design we developed a detailed computer model of our submarine. Nearly every component of the design was modeled to optimize placement and create an organized layout.

In a project that requires a great deal of planning before implementation, PTC Pro/Engineer enables our mechanical development team to visualize potential problems and allows for open discussion of possible solutions. Pro/E was also invaluable in helping us estimate weight, volume, and balance.

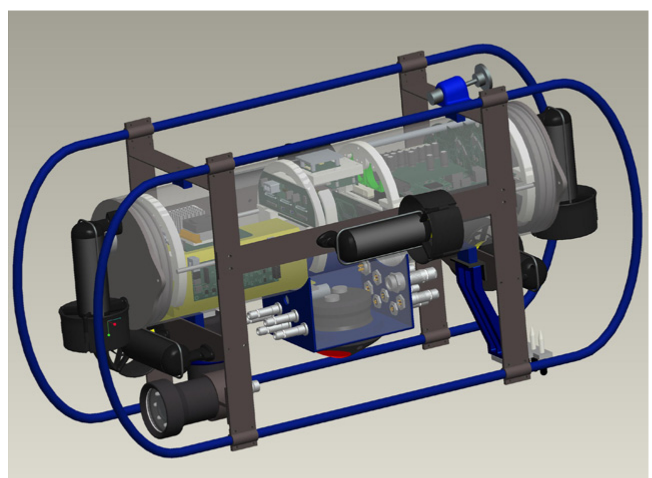

Figure 1 - CAD Rendered Image

2.2 Hull

In order to address the controllability and weight distribution problems encountered in previous years, SubjuGator's hull was completely redesigned and fabricated from scratch. A key aspect of the sixth-generation design is the principle of geometric symmetry.

Figure 2 - Hull and Hardware

The central pressure vessel is built upon a 24" long x 7" OD aluminum tube with 1/8" wall thickness. The larger body of the new generation hull allows more room for electronics and sensors, while increasing the stability of the platform while submerged. By being less susceptible to external disturbances, the submarine's control system becomes more robust. By implementing a larger platform, we have greater flexibility in the addition of future sensor packages required for additional research. When we added more advanced sensors, we required more buoyancy to compensate for the additional weight.

Our team desired to increase the maximum operating depth of our vehicle, so aluminum was chosen as the primary construction material. Aluminum has better machining characteristics when compared to the polycarbonate of previous years, and it will extend the runtime of our vehicle by permitting more efficient heat dissipation from the electronics into the water.

The end cap design of the SubjuGator was driven by the desire to implement a reliable, repeatable, and quickly deployable system. Both caps implement a double o-ring sealing system that is fault-tolerant to the repeated opening and closing of the vehicle during development. The caps are locked to the submarine using guide holes that align with complementary holes on the hull. Threaded stainless steel rods are fed into these guide holes and wing nuts are used to complete the seal of the system. The forward-facing end cap includes a port to integrate a TriTec Altimeter for ranging and obstacle avoidance/detection.

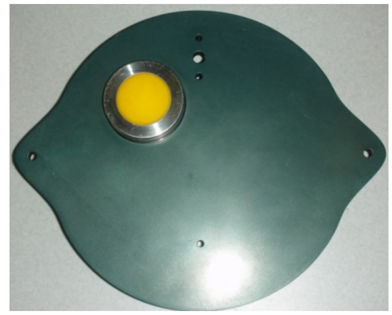

Figure 3 – End Cap with Altimeter Installed

The entire SubjuGator, including external sensors, is protected by a cage that is constructed from a hybrid carbon fiber and aluminum tube superstructure. This makes our AUV rigid, lightweight, and easy to handle. In addition, the cage protects the submarine from unintended collisions, eliminates the need for a stand, and provides a frame for the attachment of temporary or experimental sensors.

All composite parts are made using multiple layers of 3K preimpregnated carbon fiber weave. The number of layers used was dependent on the location of the support structure and how much equipment would be mounted to it. After each part was formed to its custom mold, it was covered in a vacuum bag that applied 30psi of vacuum, and then placed into the curing oven set for a 6 hour curing cycle. After each piece was cured, it went through a wet sanding process to give each piece a shiny glasslike finish.

2.3 Internal Layout

SubjuGator implements a symmetric two-sided design to facilitate the easy assembly and removal of the internal electronics. This aspect of our AUV proved very pertinent to our success. The submarine is divided in half length-wise, with the DVL positioned directly in the center. One side is dedicated to power systems and motor drivers, while the other side houses the embedded computer, the sensor interface electronics, and DVL electronics. Both sides of the platform contain removable electronics trays that mate with a backplane connection system. The electronic trays are accurately guided into place by a pair of rails that reliably blind mate connect to the back plane.

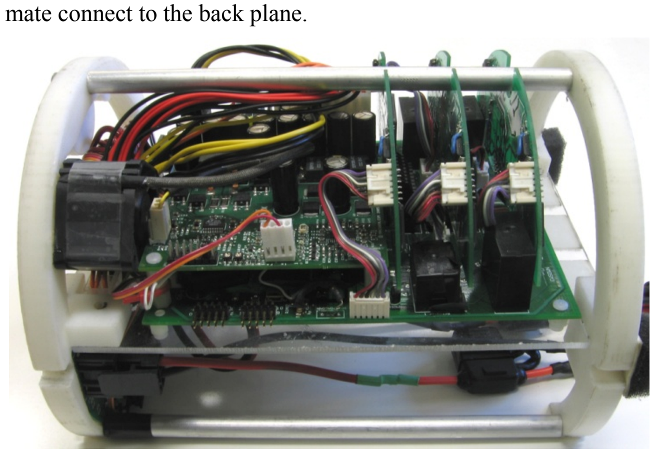

Figure 4 - Drive Electronics with Backplane

In the center of the submarine lies the DVL and through-hull connector housing. Each Fischer connector is routed cleanly to the backplane system allowing all electronics to be removed easily.

This central mechanical hub allows extremely efficient cabling between both sides of the platform and the pass-through to the external sensors and electronics.

2.4 Thrusters

All six thrusters are Seabotix SBT150 sealed thrusters with 3" diameter propellers. At 19V, these thrusters provide 6.4 lbs of thrust and pull up to 80 watts. Each thruster weighs 1.5 lbs, adding 9 lbs to the total weight of the submarine. The thrusters are rated for a depth of 500 feet. For safety, each thruster is shrouded to prevent accidental blade contact.

For ease of controllability, the thruster arrangement was designed to be as symmetric as possible. Six thrusters were implemented to give SubjuGator the most effective axis' of motion. Two depth and pitch control thrusters are mounted vertically on the end caps. The control and power cables for these thrusters pass directly through the end caps, which reduces wet plug requirements and external cabling. By making these thrusters as far apart as possible, pitch can be controlled more precisely.

The two forward/reverse thrusters are attached to carbon fiber mounts on the cage. These thrusters are positioned in the geometric center of the platform for ease of control. The laterally mounted thrusters provide strafing capability which our team has found to be a major advantage in both heading control and object tracking.

2.5 Through-Hull Connections

All of SubjuGator's through-hull connections use Fischer Connectors hermetic locking plugs and receptacles. All fourteen connectors can be used underwater to a depth of 80 meters. The most unique connector passes four RG-178 coaxial cables for the hydrophones through the hull. The devices connected are four (out of six) thrusters, shore-power, hydrophones, ball droppers, kill switch, Ethernet, two cameras, and two spare port for future expansion.

Figure 5 - Fischer Wet Plugs

2.6 External Camera Mounting

SubjuGator's external cameras utilize custom designed aluminum housings with Matrix Vision mvBlueFox-120a color USB camera and Pentax 4mm f/1.2 CS-mount lenses. The two USB cameras used this year provide the AUV with better resolution and faster frame rates than any previous generation.

The design of the camera housing was driven by our team's desire to extend the operational depth of the submarine deeper than the limits of the AUSVI competition and keep the additional weight low.

Figure 6 - Camera Housing and Mount

The housings are machined with from aluminum with a 5mm wall thickness. The flare at the window end of the housing provides room for a LED array capable of providing up to 256 cd of light. The housing was also designed to be customizable to other cameras. Both the camera electronics and lens package are housed in a plastic cartridge built using rapid prototyped parts. New or different packages can be integrated into the housing simply, with very little design and manufacturing labor hours.

Both cameras are statically mounted to the exterior of the sub. The forward-facing camera is mounted using a custom carbon fiber mount. The downward-facing camera is mounted with custom designed rapid prototyped parts. The mounting mechanism utilizes a friction lock hinge that is adjustable from -15 degrees to +25 degrees off of perpendicular, and is marked in 5 degree increments to allow repeatable orientation.

2.7 Marker Dropper Mechanism

The dropping mechanism was designed to safely carry and deliver two markers to the active target and release them when the target is detected to be orientates. The markers selected for use on SubjuGator have been radically redesigned to help divers in recovery after deployment. The marker was designed to pulse a 1Hz red light after being released from its launcher. The light circuit is energized once the marker has been ejected from its solenoid and away from the magnetic fields of the permanent magnet.

The dropping mechanism is mounted externally on the bottom of the submarine. The dropper was designed to utilize a permanent magnetic for marker retention. This mechanism also uses a hand wound DC coil to cancel the magnetic field and eject the marker.

3. Electronic Hardware

3.1 Batteries

SubjuGator uses two MaxAmps 14.8V, 10Ah lithium polymer battery packs. One pack powers the electronics, embedded computer, and sensors. The second battery is dedicated to the thrusters. Each pack is made of four 10Ah lithium polymer cells connected in series. Lithium polymer chemistry batteries are preferable over other battery chemistries because of their higher energy density and lower cell count. Each pack is rated to continuously source up to 150A. Since the submarine's thrusters will draw a maximum of 24A, the batteries will produce a very linear voltage until the pack is depleted. This will allow the submarine to provide the same performance throughout the life of the battery.

In order to estimate runtime figures, we consider the limiting battery pack: the thruster power source. The absolute worst case runtime is estimated to be 25 minutes. This circumstance is calculated by considering all 6 thrusters drawing a 4 amp maximum, producing a continuous 24A maximum current draw. In typical application the SubjuGator is capable of running over three hours uninterrupted.

3.2 Computing

The wide variety of computing challenges posed by autonomous underwater robotics requires the SubjuGator to use a diverse mix of processing systems to accomplish its goal.

3.2.1 Embedded x86 Computer

Major emphasis was placed on selecting an embedded computing solution that offers the highest performance available while being very power efficient. Intel's Core 2 Duo processors provide the best performance/watt ratio of any x86 processor available to date. Finding a Single Board Computer (SBC) motherboard capable of implementing this processor into our design proved to be quite a challenge. Eventually our team selected the LS-371 from Commell Industrial Computer.

The specifications of our embedded computing solution are as follows: Intel T7600 Core 2 Duo 2.33GHz CPU, 2GB of 533MHz DDR2 RAM, and a Seagate 80GB 7200rpm SATA hard disk. This hardware runs the Microsoft Windows Server 2003.

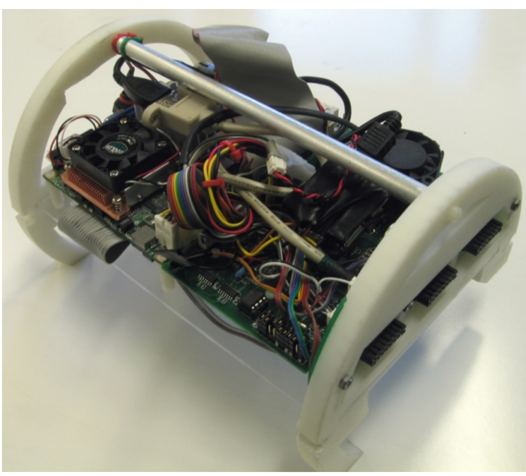

Figure 7 - Embedded Computer Tray

Being one of the first groups to use this specific computer setup led us to discover a design flaw in the LS-371. Working with Taiwan based engineers at Commell, we discovered that two inductors in the CPU power regulation circuit could not handle the amount of current required by our CPU under 100% load. Commell sent us the necessary parts to repair the problem and we have since experienced no problem with the operation of our embedded PC.

This computer is also the central point of our vehicle's sensor information and control system. Microsoft Robotics Studio (MSRS) is installed on this single node and coordinates all transactions between the various sensors.

3.2.2 Sensor Interface and Communication

The Sensor Interface and Communication PCB (SICPCB) is implemented to organize the flow of information between most of SubjuGator's sensor packages and the main computer. By utilizing four FTDI FT232D Dual UARTs interfaced directly to an embedded 4-port USB hub, our computer can communicate with eight individual serial sensors over a single USB 2.0 connection. This greatly reduces cable clutter and expands the serial communication capabilities of our computer tremendously.

This board also directly hosts three important environmental monitoring sensors that continuously sample statistics such as temperature, pressure, humidity, and the presence of liquid in the hull. These sensors are the SHT15 humidity sensor from Sensirion and the SCP1000 pressure sensor from VTI. The liquid leak detectors are custom designed to monitor for any small amount of standing water that would collect in the event of an O-ring failure. Two isolated leads are configured into a voltage divider network and are monitored with the ARM7 A/D converters. The leads are then strategically placed so that any standing water would short the contacts and provide a large change in the A/D output register value.

By giving our vehicle the capability to constantly monitor for trouble, we can choose to abort the mission and preserve the integrity of our electronic systems in the event of a structural failure.

3.2.3 Microcontrollers

In stark contrast to previous generations, the SubjuGator contains no Atmel microcontrollers. The two microcontrollers used in the submarine are Philips LPC ARM7 variants. These are used in two places to interface the depth sensor to DVL and to interface the environmental monitoring sensors to the PC.

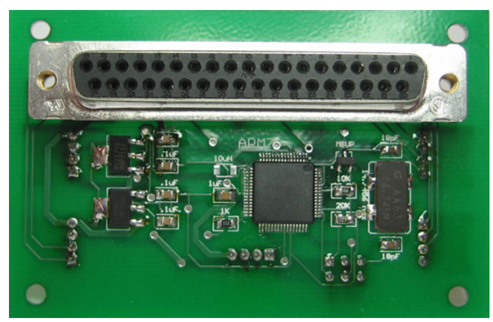

Figure 8 - DVL Interface and ARM7

In addition, we have also implemented a backup command and control interface through one of these ARM7 microcontrollers to bypass the PC in the event a failure was incurred. Although this feature is still very primitive, our hope is to expand this capability into a redundant control system in emergency situations.

3.2.4 Altera FPGA

Two Altera Cyclone II EP2C8 FPGAs are utilized: one in the hydrophone data acquisition system and one in the motor driver control system. FPGAs are extremely versatile and allow a tremendous amount of customization to these systems.

The motor control system uses the FPGA to generate all of the PWM signals for motors and actuation control signals. This FPGA is the interface between the PC and the drive system's electronics.

The FPGA in the hydrophone data acquisition system is used for parallel data acquisition of all four passive sonar channels. After acquisition, the data is filtered and uploaded to the PC for final processing.

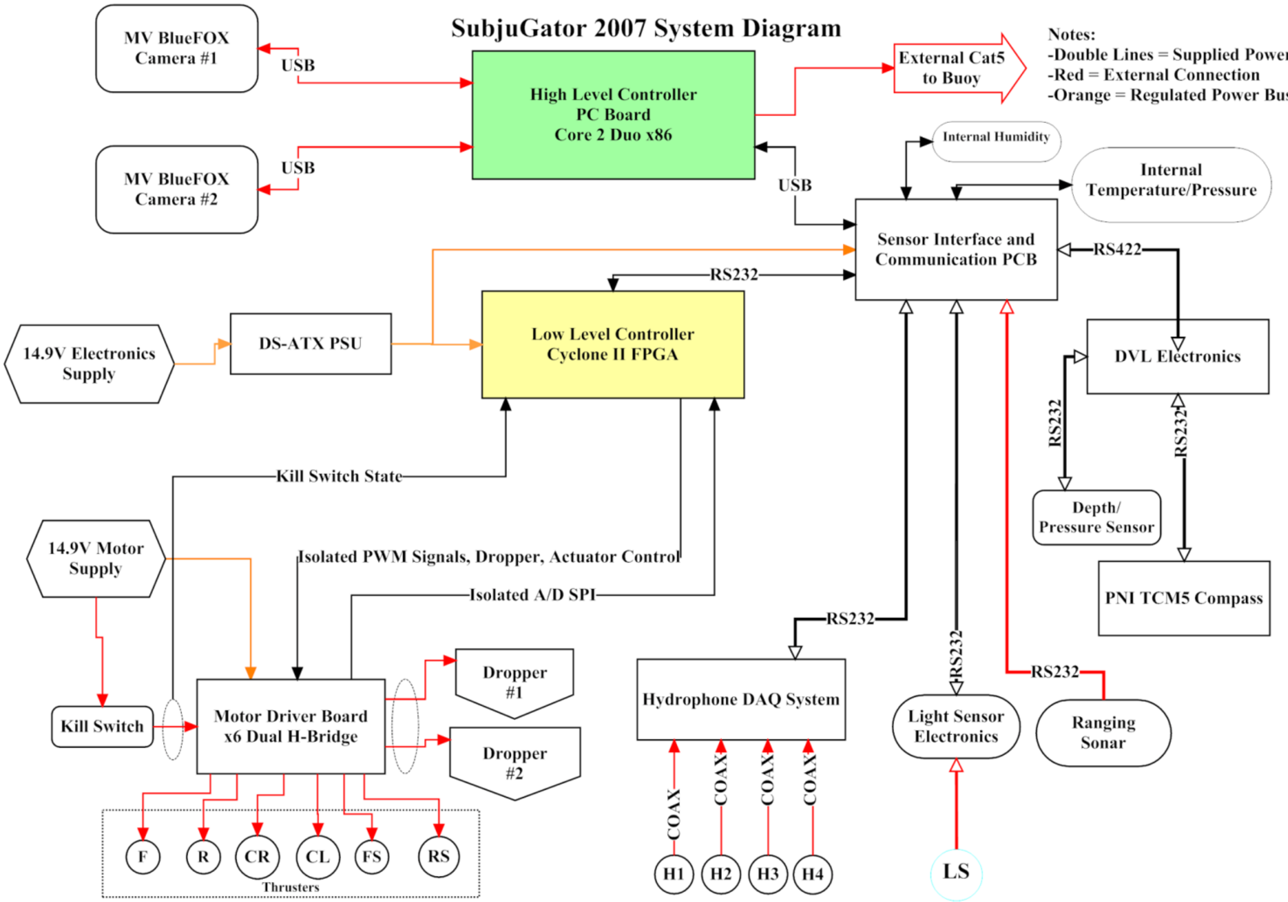

Figure 9 - SubjuGator System Layout

3.2.5 Wireless System Access

A communications interface between a base station and a floating buoy utilizes a wireless Ethernet (802.11b/g) connection with up to a 108Mb/s data path. The buoy is tethered to the submarine with CAT5e Ethernet cable to a Fischer plug directly into the Ethernet port on the PC. This connection allows remote access to SubjuGator's computer, file share, and simultaneous programmer access for parallel code development and debugging. By viewing the real-time sensor data, we can tune most aspects of the submarine's intelligence and control, including PID coefficients and arbiter modes. This communication link is only available when the floating buoy is tethered to the submarine.

3.3 Navigational Sensors

For even the most basic operation, an AUV must be able to maintain a heading, depth, and attitude. Regardless of mission specific operations these sensors provide basic AUV control.

3.3.1 Doppler Velocity Log

The Doppler Velocity Log (DVL) is an all-inclusive acoustic sensor that integrates with the magnetic compass, pressure sensor, and temperature sensor to produce precise velocity and position information. Each of the four transducers of the DVL emits a 600 kHz acoustic ping. Doppler techniques are then used to calculate instantaneous velocity relative to the sea floor. The DVL computes a 3-dimensional velocity vector with an error velocity, and from an initial position, can integrate the velocity over time to provide a 3-dimensional distance vector. The DVL sends a complete data packet with this information over a 115k baud RS-422 serial connection at a 10Hz sample rate to the SubjuGator's main computer.

The Teledyne RD Instruments Explorer DVL consists of a piston transducer head connected to an electronics chassis by a pair of transmit and receive cables. A custom flush-mount circuit board connects 2 RS-422 serial interfaces, 2 RS-232 serial interfaces, and power to the DVL electronics enclosure.

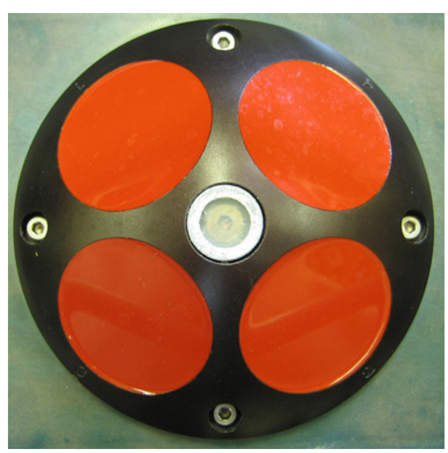

Figure 10 - Doppler Velocity Log Transducer

3.3.2 Digital Compass

SubjuGator uses a TCM5 compass from Precision Navigation. This compass is rigidly mounted near the geometric center of our vehicle. Comprised of a tri-axial magnetometer and a microprocessor, this compass generates heading, tilt and roll information throughout its operational range. This sensor interfaces directly with the Explorer DVL which processes and combines the compass data with its feedback information

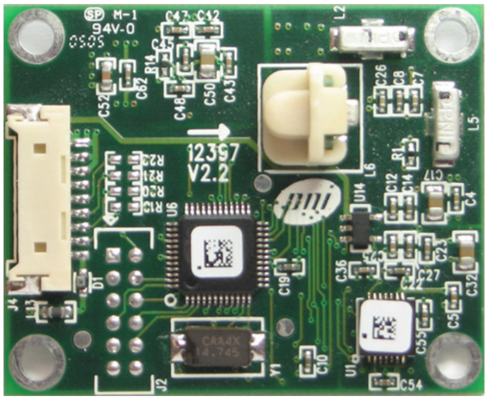

Figure 11 - TCM5 Compass

The compass provides a set of outputs that, when combined with a subset of the desired parameters, determine some of the error inputs to the PID controller.

3.3.3 Depth Sensor

The Desert Star SSP-1 sensor combines temperature and pressure in a NMEA-0183 data structure over RS-232 serial. The DVL only supports 2 pressure sensor models, both out of our price range, so we emulated the Paroscientific 8CDP pressure sensor on an ARM7 microcontroller with the SSP-1. The DVL implements only 32 of the 76 Paroscientific commands, so we only needed to match the request and response of each of those commands on the ARM. The SSP-1 has a maximum output of 16 Hz, so the ARM averages the last 4 samples and always keeps the most recent value available for the DVL.

3.4 Mission-Specific Sensors

To complete the mission objectives, our AUV needs sensors specific to each of the three tasks. The first objective is to maintain a steady heading and pass through the starting gate.

After passing under the gate, the submarine must locate and hit a simulated docking station. The docking station is represented by an omni-directional ground moored light source and can be dislodged by tapping with the submarine.

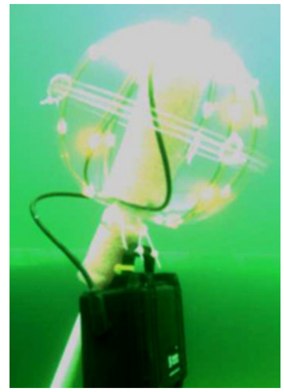

Figure 12 - Docking Station

To complete the third task, the submarine needs to drop two markers in the target bins located along the pipe segments. The pipeline is represented by orange PVC panels and the target bin by a black 1’ x 2’ rectangular box inside a white 2’ x 3’ rectangular box.

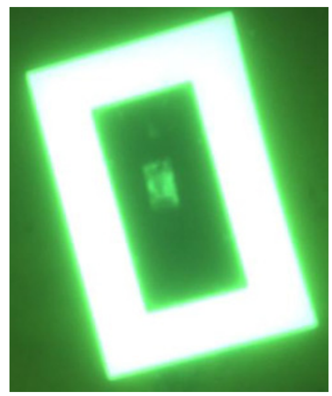

Figure 13 - Target Bin

Lastly, submarines must locate and retrieve from the bottom a submerged PVC structure. The X-shaped object is marked with an acoustic pinger that resonates at approximately 25 kHz.

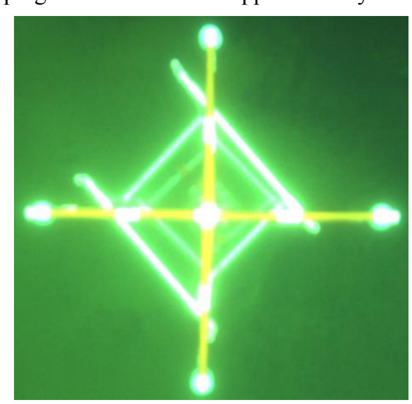

Figure 14 - X Marks the Treasure

The final task requires submarines to surface in one of two 9’ diameter octagonal surface zones. While there are two surface zones, containing the treasure, each with a pinger, only one pinger is activated during the competition run. Thus there is only one correct surface zone.

3.4.1 Hydrophone System

The hydrophone system consists of four basic stages that aid in obtaining and processing the signals transmitted by an acoustic pinger:

1. Acoustic Transducer
2. Analog Filter and Amplifier
3. Data Acquisition
4. Digital Signal Processing

The hydrophone system provides a means with which to detect acoustic vibrations in the water, such as the signals transmitted by the acoustic pinger corresponding to the surface zone. SubjuGator utilizes four hydrophones mounted in a planar configuration resembling letter T to create the geometry needed to identify the direction and distance from which the received signals originated.

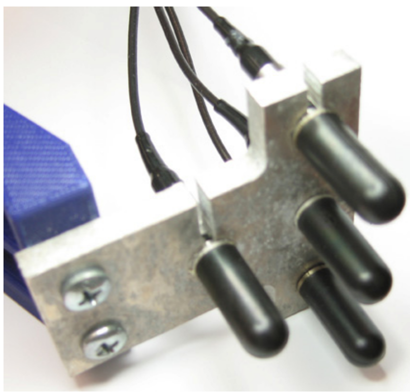

Figure 15 - Hydrophone Array

The hydrophones provide a voltage representing the strength of the acoustic signal. To clean up the signal, we filter out all frequencies outside 19 to 31 kHz using a 2nd order passband analog filter. The filtering removes low and high frequency noise present in the signal.

Data acquisition is controlled by an onboard FPGA. The FPGA samples all four hydrophones simultaneously at a rate of 250 kHz. The data is stored in local memory and shifted out serial to the onboard computer. Digital signal processing is done utilizing MATLAB to determine the time of arrival difference between the sampled signals. The time of arrival allows us to determine the relative angle and distance between the submarine and the acoustic pinger.

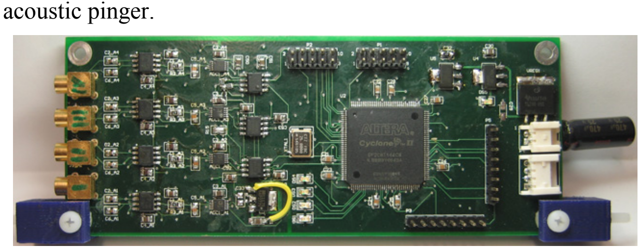

Figure 16 - Hydrophone Signal Processor

4. Software and Controls

4.1 Software Architecture

Our team is using the newly released Microsoft Robotics Studio (MSRS) as the software framework for the SubjuGator. MSRS is a service-oriented architecture based on Microsoft's Coordination and Concurrency Runtime (CCR) and the Decentralized Software Services Protocol (DSSP). This combination allows the seamless implementation of large scale multi-processor applications. We are enabled to handle asynchronous inputs from multiple sensors, which control the output behaviors via motors and actuators.

MSRS is essentially a collection of custom services (independent programs running concurrently), each with a set of predefined input/output messages. This allows each service to run with a defined behavior while asynchronously reacting and responding to incoming messages. Messages are sent using an XML serialization standard. Messages can be processed locally on the same computer or transmitted via TCP/IP without making any code changes. As a result, all service applications can be run on the single local computer, or split off to any computer connected to the internet.

In the case of the SubjuGator, where space and power consumption are limiting factors, our complete service architecture runs on a single dual-core CPU. However, SubjuGator 2008 is on track to contain two dual-core computers.

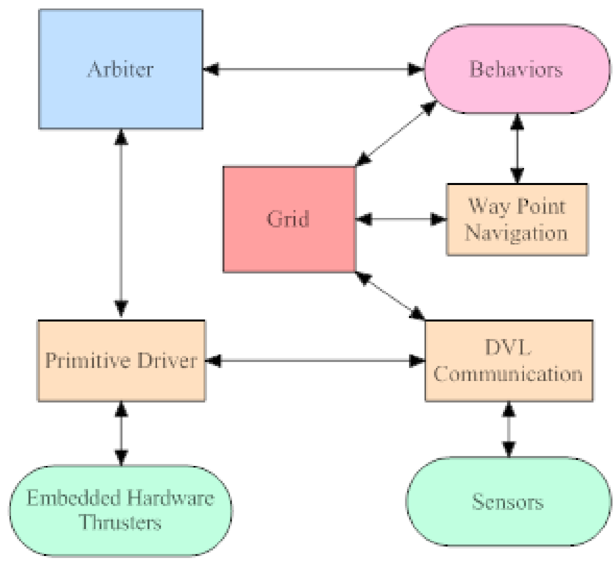

Figure 17 - High Level System Architecture

At present, our architecture consists of a collection of over 15 independent services. This includes an Arbiter service, which is responsible for dictating the mission and deciding which behaviors should be running at any given time. We have also implemented a "grid" service, which is used to collect all of the SubjuGator's sensor data into one organized location. The grid constantly broadcasts the state of the SubjuGator to all services subscribed to the grid. The grid can also respond to a custom request message sent by any service. There are a host of behavior specific services, which are each responsible for completing a given predefined task, such as passing through the gate, finding and following the pipe, ramming a buoy, etc. The final set of services is dedicated to communications with the embedded hardware, sensors, and thrusters. These services are focused on updating data in the grid immediately. Once in the grid, the data is formatted and stored for use by the behavior services.

4.2 Attitude Control Systems

Control of the submarine is implemented in the primitive driver service. This service is responsible for feedback control of pitch, roll, heading, depth, and speed using multiple proportional, integral, derivative (PID) based controllers. Feedback is attained through the depth sensor, Doppler velocity log, motor current sensors, and compass. These sensors allow the SubjuGator to measure many of the states needed to effectively control its attitude in the water. The measured states are the three translational velocities, yaw position, pitch position, roll position, approximate motor thrust, and the depth at the pressure sensor. Control of these states is simplified by decoupling pitch and depth control from roll and yaw control by assuming that the two do not interact. Although this assumption is obviously invalid, it has been found to be an acceptable compromise, as long as pitch and roll are fixed at zero in the algorithms. Position control is implemented in the form of 6 independent PID algorithms, one for each thruster. Velocity control is also implemented in a separate PID algorithm, which is then fed forward as an additive term to the right and left thruster loops. All of these control loops are running at 10Hz. Control inputs to the primitive driver service are sent from the Arbiter Service.

The continuous PID equation is converted to its discrete-time equivalent and the errors are calculated from the difference between the current and desired yaw, roll, pitch, and depth, using the following equation:

$$m(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

In the above equation, m(t) represents the motor value and e(t) represents the error at time step t. The individual gains (K_p, K_i, K_d) are tuned through repetitive testing at various depths and operating conditions. These parameters are determined through experimentation and simulation. (Figure 18 shows the submarine in the water during the tuning of these control parameters.)

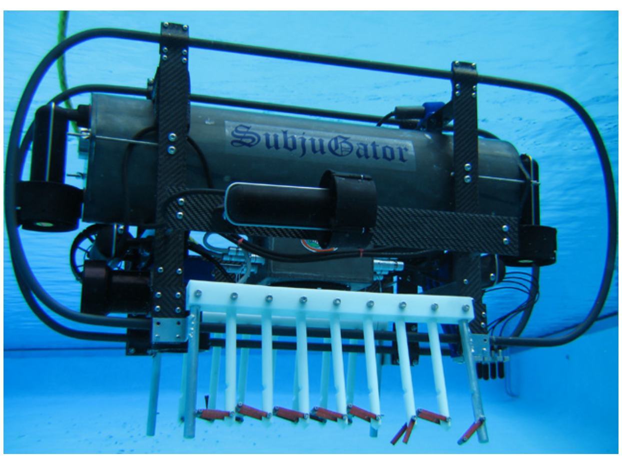

Figure 18 - Testing and Tuning Motor Control

4.3 Arbiter and Behavior Services

The service-based architecture of MSRS is a very powerful concept and has been put to use in the implementation of the high-level control for the SubjuGator. The behavior services consist of individual software components that evaluate sensor feedback and make recommendations to the arbiter concerning each of their areas of responsibility. The main behaviors for the AUVSI competition are pipe following, buoy tracking, and pinger acquisition. The arbiter service is essentially a dynamic state machine that is defined at initialization by a script file containing mission specific parameters. The arbiter will control the behavior that can exert control over the submarine at any single instance in time. However, all behaviors are constantly making recommendations, allowing the arbiter to prioritize control based upon a priori defined mission parameters. The architecture is analogous to a board of directors, the chairman of the board being the arbiter and the members each being a behavior. At all times different members are making their assessment of the situation known to the chairman, while the chairman makes the final decision regarding which recommendation to implement. This process allows for a truly modular and expandable infrastructure which should support many future missions by just the addition of a new behavior to handle the future task.

4.4 Computer Vision System

The onboard computer takes in video feeds from two USB cameras. One is permanently mounted pointing forward, in a carbon fiber holder. The second is mounted in a rapid prototyped adjustable-angle clamp, pointing downward for all of the missions.

Using the downward camera, the submarine searches for the pipeline. To find the pipeline, we characterize the image using a pre-trained Gaussian Mixture Model (GMM),

$$p(x \mid \theta) = \sum_{k=1}^{n} w_k N(x, \mu_k, \Sigma_k),$$

where n represents the number of Gaussians in the model, μ the mean, ∑ is the variance, and w is the weight of the k^{th} Gaussian component.

The multi-dimensional Normal function, N, is defined as,

$$N(x, \mu, \Sigma) = \frac{1}{2\pi |\Sigma| \frac{D}{2}} \exp\left(-\frac{(x-\mu)^{\mathrm{T}} \Sigma^{-1} (x-\mu)}{2} \right)$$

A GMM is trained for each of the four major classes of objects to be encountered in this stage of the competition: Water/pool floor, pipeline, drop zones, and X recovery. While the training of a single Gaussian can be done using Maximum-Likelihood Estimation, multiple Gaussians have no closed-form solution and require the EM (Expectation-Maximization) Algorithm to iterate to a solution. The EM algorithm guarantees the convergence of the model's parameters, θ, to a local maximum.

The GMMs generated in training are then continuously evaluated during the mission. Once a significant mass of pipe is found, a Canny edge filter is applied to find the edges of the pipeline. The edge image is then used by a Hough Transform to find the orientation of the lines. The orientation of the pipe relative to the submarine's current orientation provides a new offset heading for the submarine to follow.

To avoid confusion in variably-lit environments where colors can appear similar and less substantial intensity changes can obscure edges, SubjuGator employs a blob analysis to detect bins and calculate their center of mass. The analysis is implemented using an algorithm of run length encoding followed by a pairwise line splicing.

The pipeline is followed until a break in the pipeline is discovered using the same Gaussian modeling procedure. The angle of the stripes relative to the angle of the pipeline determines whether the submarine ignores the bin or attempts to drop the ball in the bin. If the correct bin is detected, the sub attempts to center itself over the center of mass of the bin. Once over the bin, the two markers are released using the solenoid described in section 2.7.

5. Acknowledgements

We would like to thank Harris Corporation, Lockheed Martin Corporation, Intel Corporation, UF's College of Engineering and UF's Department of Electrical and Computer Engineering for their continued and substantial support of Team SubjuGator. We would also like to thank Altera, the Gainesville section of IEEE, Microsoft, Dundas Data Visualization, and Fischer Connectors. We would especially like to thank our faculty advisors for all their support, encouragement, and advice. Thanks also go out to the previous SubjuGator team members who have contributed to the legacy of SubjuGator. Finally, we are grateful to the many other members of the Machine Intelligence Laboratory (MIL) who have helped over the last year with our submarine.

6. REFERENCES

[1] Dempster, A. P., Laird, N. M., and Rubin, D. B. Maximum Likelihood from Incomplete Data via the EM Algorithm. *J. Royal Statist. Soc. B-39*, 1–38, 1977.

[2] Perona, P. and Malik, J. 1990. Scale-Space and Edge Detection Using Anisotropic Diffusion. *IEEE Trans. Pattern Anal. Mach. Intell.* 12, 7 (Jul. 1990), 629-639.

[3] Clare, C.P., "Acoustic Direction Finding Systems," U.S. Patent 4 622 657, November 11, 1986.

[4] Rogers, R. M. 2000 *Applied Mathematics in Integrated Navigation Systems*, AIAA (American Institute of Aeronautics & Ast.), 2000.

[5] Dorf, R. C. and Bishop, R. H. 2000 *Modern Control Systems*. 9th. Prentice-Hall, Inc.

[6] Evans, Ken. R. 2001. *Programming of CNC*. 9th. Prentice-Hall, Inc.

[7] SubjuGator 2006. Carlo Francis, James Greco, Kevin Claycomb, Matthew Koenn, Sean Cohen, Sean Matthews, Michael Gregg, Jacob Collums, Gene Shokes, Greg Cieslewski, Adam Barnett, Eric M. Schwartz. Association for Unmanned Vehicle Systems International, July 2004.