SubjuGator 2007

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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 in the process of completing the sixth generation of their autonomous underwater vehicle, SubjuGator, to compete 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 single-board Intel Core 2 Duo based computer running the Windows XP operating system provides processing power necessary for monitoring and controlling all systems. The mission behavior of SubjuGator is controlled with Microsoft Robotics Studio framework communicating with a network of intelligent sensors. The sensor systems include cameras, hydrophones, a Doppler Velocity Log (DVL), a digital compass, altimeter, and internal environment monitoring sensors. The submarine also makes use of custom designed motor controllers with current feedback monitoring and other peripherals necessary for completing the mission. In this paper, we will first describe the construction of the SubjuGator hull and other 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) are sponsoring the tenth annual international autonomous underwater vehicle competition to be held in San Diego, California at the SPAWAR facility July 11th through July 15th. A student team at the University of Florida is once again developing an autonomous underwater vehicle (AUV) for this year's contest. SubjuGator has been completely redesigned to not only meet the new challenges of the competition, but also engage in new 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 segmented line along the bottom to find a target bin. Ideally, the robot will release the second buoy revealing the target bin and drop 1 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 determine the best placement, and to permit an organized layout.

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

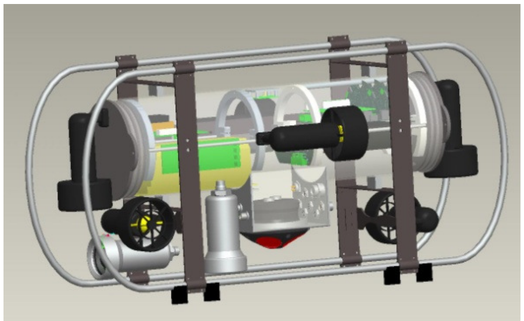

Figure 1- CAD Rendered Image

2.2 Hull

In order to address problems of controllability and weight distribution encountered in previous years, SubjuGator's hull was completely redesigned and fabricated from scratch. A key aspect in the design this year 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 this year's hull allows more room for electronics and sensors, as well as the potential to increase 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 are given greater flexibility in the addition of future sensor packages required for additional research. With the addition of the DVL and other advanced sensors we required more buoyancy to compensate for the additional weight.

Our team desired to extend the maximum operating depth of our vehicle so aluminum was chosen as the primary construction material. Aluminum has better machining characteristics when compared to polycarbonate and 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 fastened to the SubjuGator using guide holes that are aligned with complementary holes on the hull. Threaded Stainless rods are fed these guide holes and finger turnable 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.

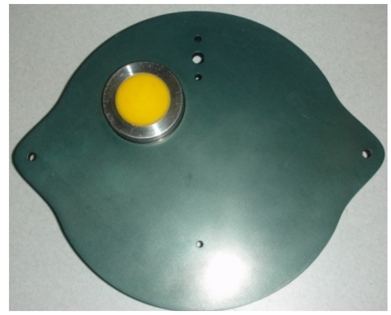

Figure 3 - Endcap with Altimeter Installed

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, light weight, and easy to handle. In addition, the cage protects the submarine from unintended collisions, eliminates the need for a stand, and allows a frame for the attachment of temporary or experimental sensors.

All composite parts are made using multiple layers of 3k prepreg. carbon fiber weave. The amount of layers used was dependant on the location of the support structure and how much equipment would be mounted to it. After each piece was placed in its mold it was covered in a vacuum bag and that applied -30psi of vacuum and placed into the curing oven set with a 6hr 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 to be very pertinent to our success. The submarine is divided in half lengthwise, with the DVL 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 set of rails that facilitate a reliable blind-mate connection to the back plane.

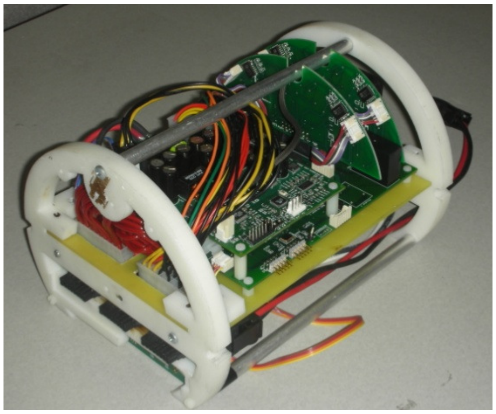

Figure 4 – Drive Electronics with Backplane

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 require 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 to 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 4 RG-178 coaxial cables for the hydrophones through the hull. The devices connected are 4 (out of 6) thrusters, shore-power, hydrophones, ball dropper, claw grabber, kill switch, Ethernet, both cameras, a color sensor, and one spare port for future expansion.

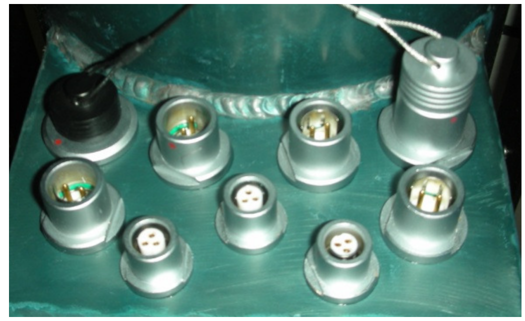

Figure 5 - Fischer Wet Plugs

2.6 External Camera Mounting

SubjuGator's external cameras utilize custom designed aluminum housings with Pentax 4mm F 1.2 CCTV CS mount lenses coupled to the internal electronics of the Matrix Vision mvBlueFox-120A color USB-2.0 camera. These 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 two our team's desire to extend the operational depth of the submarine deeper than the limits of the AUSVI competition.

Figure 6 - Camera Housing and Mount

The housings are made using 5mm thick aircraft structural aluminum. The flare at the window end of the housing provides room for a LED array capable of providing up to 256cd of light. The housing was also designed to be customizable for other cameras. Both the electronics and lens package are housed in a plastic cartridge built using rapid prototype 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 prototype 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 dropping 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. 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 ball.

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 two 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 HDD. This hardware runs the Microsoft Windows XP Professional OS.

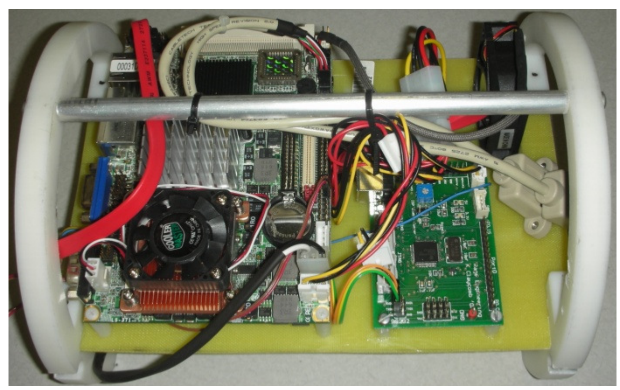

Figure 7 - Embedded Computer Tray

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.

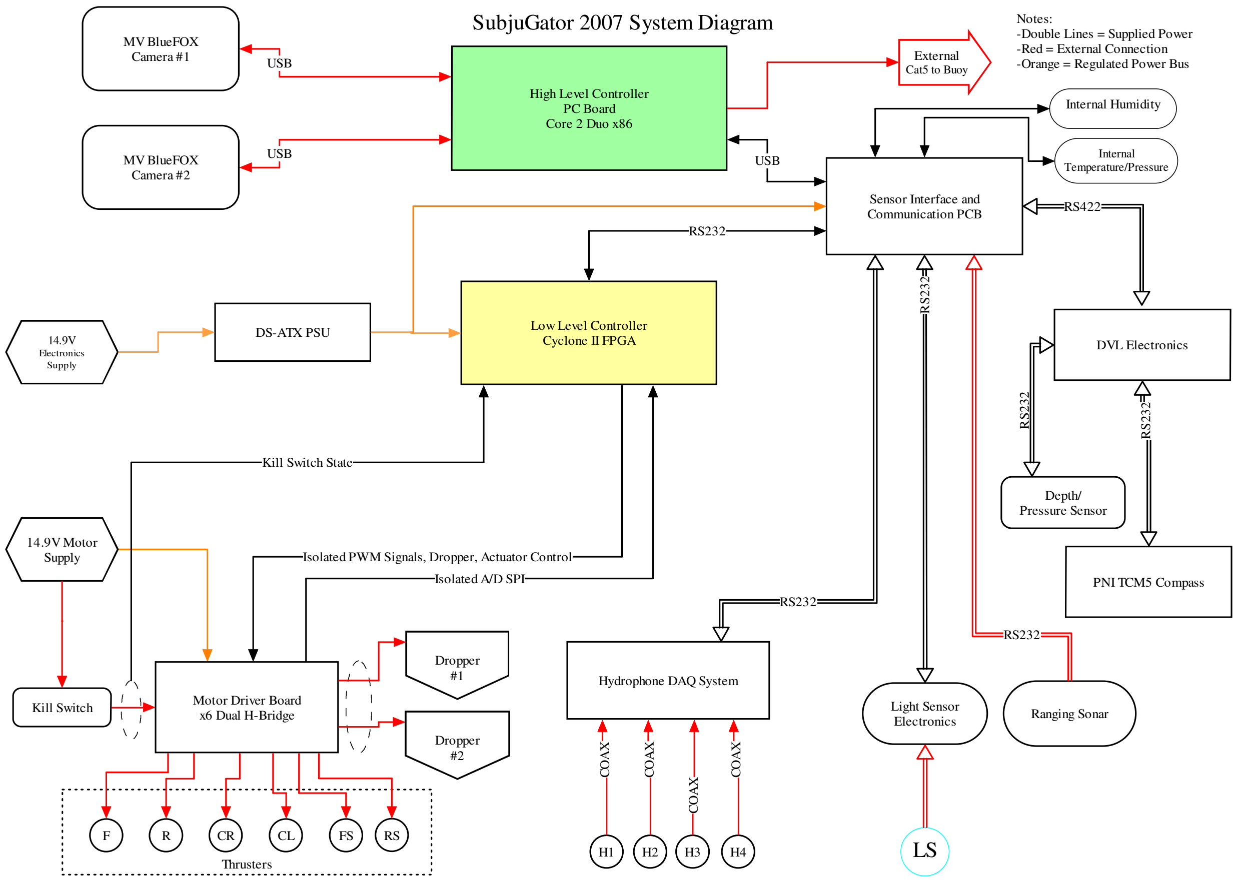

Figure 8 - SubjuGator System Layout

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 hub, our computer can communicate with eight individual sensors over a single USB 2.0 connection. This greatly reduces cable clutter and expands 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 failure.

3.2.3 Microcontrollers

In stark contrast to previous generations, the subjugator contains no Atmel microcontrollers. The two microcontrollers used in the sub 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.

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 2 EP2C8 FPGAs are utilized in the hydrophone data acquisition system and 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, actuation control signals, and current feedback. 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.

3.2.5 Wireless system access

A communications interface between a base station and a floating buy utilizes a wireless Ethernet (802.11b/g/n) connection with up to a 108Mb/s data path. The buoy is tethered to the submarine with CAT5e Ethernet cable to a through-hole connection directly into the Ethernet port on the PC. This connection allows remote access to SubjuGator's computer, FTP, 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 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. By adding these velocity vectors internally, the DVL outputs a 3-dimensional distance vector traveled with error. 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.

Figure 9 - Doppler Velocity Log

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.

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

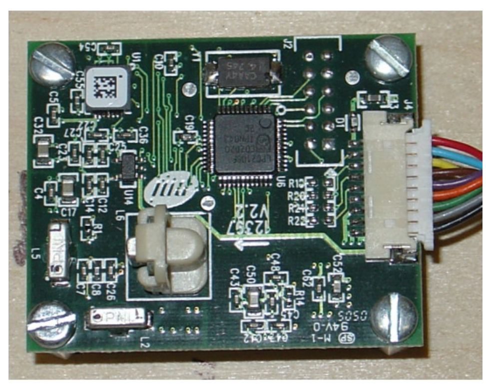

Figure 10 - TCM5 Compass

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 will need sensors specific to each of the three tasks. The first objective is to hold a steady heading and pass under the starting gate.

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

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.

The final task requires submarines to surface in one of two 9' diameter octagonal surface zones. The correct surfacing zone is marked by an acoustic pinger resonating at a specific frequency every couple of seconds.

3.4.1 Color Sensor System

Detection and classification of the signal is done using 4 Taos color sensors (TCS230) that outputs the detected intensity of red light. This output is a frequency modulated signal, ranging from approximately 100kHz to 600kHz. An FPGA is used to sample this sensor by simply counting the time between rising edges on the output. This is sampled into a microcontroller at a rate of 50kHz. The microcontroller takes the inverse of the count value, providing a frequency that corresponds to the intensity value.

An IIR resonance filter is then applied to the intensity values to determine the frequency of the blinking light. The filters will be band pass filters with a tight pass band centered at 2 kHz or 5 kHz. The average magnitude of the time-domain output is computed for green, blue, or red light, filtered at 2 kHz and 5 kHz. However, the values between the three colors cannot be directly compared due to differences in intensity of the ambient light for these colors. Instead, the ratio of the maximum of the two frequencies for each light to the minimum is computed, and these ratios are compared. The ratios are also compared to a threshold to ensure that the light box is actually in view.

The resonance filters used are 2nd order. The impulse responses of the filters are shown in Figure 7.

3.4.2 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.

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 pass-band analog filter. The filtering removes low and high frequency noise present in the signal.

Figure 11 - Hydrophone Array and FPGA Board

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.

4. Software and Controls

4.1 Software Architecture

This year, our team is using the newly released Microsoft Robotics Studio (MSRS) as our 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 application with the ability to handle asynchronous input from multiple robotics sensors which controls 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 which allows messages to be transmitted on the same computer or via TCP/IP without making any changes to code. As a result all service applications can be run on a single CPU, or can be split up allowing each service to run on a separate CPU all connected together from anywhere in the world via the internet.

In the case of the Subjugator, where space and power consumption as the limiting factors, our complete service architecture runs on a single dual-core CPU, yet could easily be split into a multi-CPU system if required in the future.

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 a given time. We have also implemented a "grid" service, which is used to assimilate all of the Subjugator's sensor data into one organized location. The grid constantly broadcasts the state of the Subjugator to all services which have 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 receiving and sending data immediately to the grid. Once in the grid, the data is then formatted and stored for use by the behavior services.

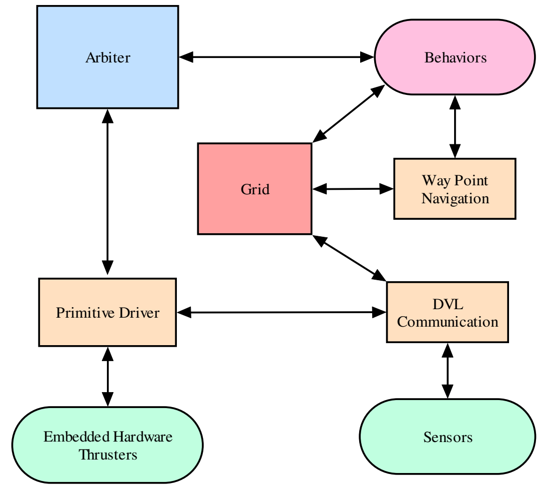

Figure 12 - High Level Software Architecture

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 unit. 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 (Kp, Ki, Kd) are tuned through repetitive testing at various depths and operating conditions. These parameters are determined through experimentation and simulation. (Figure 8 shows the submarine in the water during the tuning of these control parameters.)

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 op 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 SBC takes in video feeds from two USB cameras. Both cameras are mounted inside the transparent pressure case. One camera is mounted behind the clear acrylic end cap and the other is mounted in the back of the sub facing directly down.

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),

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

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,

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

A GMM is trained for each of the three major classes of objects to be encountered in this stage of the competition: Water/pool floor, pipeline, and the drop zones. 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 models 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 coding followed by a pair wise line splicing.

The pipeline is followed until a break in the pipelined 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 3.5.

5. Acknowledgments

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