SubjuGator 2008

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ABSTRACT

For the past eleven years, 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 undergraduate and graduate students are in the process of completing the sixth generation sixth generation of their autonomous underwater vehicle, SubjuGator, to compete in the *AUVSI and ONR's 11th International Autonomous Underwater Vehicle Competition*. SubjuGator is designed to operate underwater at depths up to 100 feet. Two 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, imaging sonar, 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.

1. INTRODUCTION

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) sponsored the 11th annual International Autonomous Underwater Vehicle Competition, held in San Diego, California at the SPAWAR facility July 29th through August 3rd, 2008. A student team at the University of Florida's Machine Intelligence Lab (MIL) developed an autonomous underwater vehicle (AUV) for the 2008 contest. Other than the main hull body, SubjuGator has been completely redesigned (mechanical, electrical, computer, and software) 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 several tasks. First, the robot will demonstrate autonomous control and orientation by passing through a validation gate. Next, the vehicle will free a start buoy that is anchored to a mooring. After this task is complete, the AUV will track multiple separated line segments along the bottom to find a set of bins with card suits in the middle. The vessel will then navigate through a tunnel. 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 safe and surface inside of the recovery zone.

2. MECHANICAL PLATFORM

As a sixth-generation vehicle, SubjuGator 6a (see Figure 1), embodies the lessons learned in the previous ten 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.

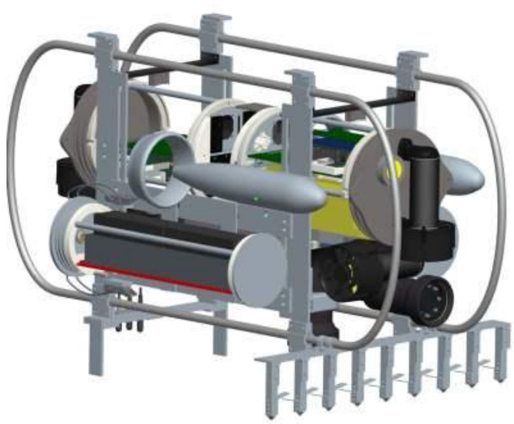

Figure 1 - CAD Rendered Image

2.2 Hull

SubjuGator's 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 provides more room for electronics and sensors, while increasing the stability of the platform while submerged. By implementing a larger platform, we also have greater flexibility in the addition of future sensor packages required for additional research.

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 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-resistant to the repeated opening and closing of the vehicle during development. The caps are locked to the submarine using threaded stainless steel rods fed through flanges. Wing nuts are used to tighten the cap along these rods, while evenly distributing the forces required for cap installation.

The entire SubjuGator, including external sensors, is protected by a cage that is constructed from a hybrid carbon fiber and aluminum 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.

2.3 Battery Pods

Vehicle runtime has been extended through the addition of external battery pods. Following the design intent of the hull, the pods are constructed of 15" long x 4.5" OD aluminum tube. Vertical tabs were welded onto each pod to allow for modular mounting with the existing aluminum superstructure. The pods allow for the electronics and thruster batteries to be removed from the central hull, providing room for more electronics.

2.4 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 sensor interface electronics, and DVL electronics. Both sides of the platform contain removable electronics trays that mate with a backplane connection system (Figure 2). The electronic trays are accurately guided into place by a pair of rails that reliably blind mate connect to the back plane.

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.

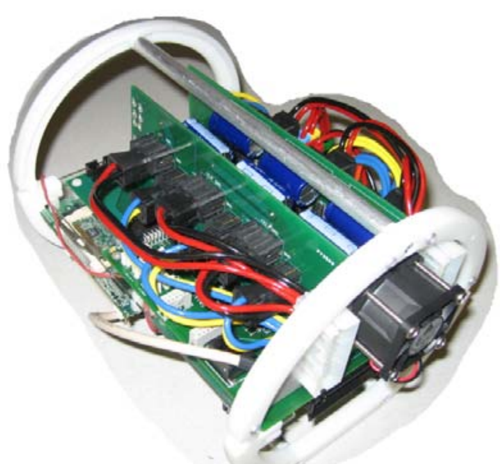

Figure 2 - Drive Electronics with Backplane

2.5 Thrusters

Four of the 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. The remaining two thrusters are VideoRay GTOs. These motors employ the same internal motor as the Seabotix SBT150, but use a gearhead transmission and hydrodynamic casing for increased efficiency.

2.6 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.

2.7 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. 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.

2.8 Marker Dropper Mechanism

The dropping mechanism (Figure 3) was designed to safely carry and deliver two markers to the active targets and release them when the appropriate target is detected.

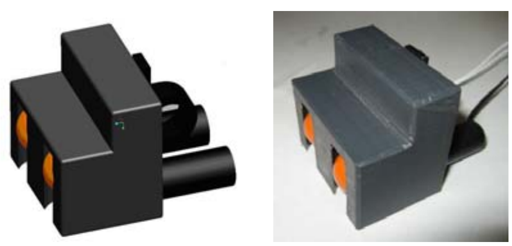

Figure 3 – Dropper CAD and dropper picture.

Constrained by size and weight, our choice of markers was to use 5/8-inch diameter chrome bearings, both for their mechanical and hydrodynamic properties. The markers were painted orange with automobile enamel for easy recognition and were imprinted with an emblem for identification. The design for the dropper mechanism was chosen to be as light and as simple as possible. A plastic block was machined to allow the simultaneous and safe transportation of the markers. To allow each marker to be dropped independently, two pull solenoids were used. By independently activating the solenoid, each individual marker can be delivered when desired.

2.9 Safe Grabbing Mechanism

In order to retrieve a safe (square PVC frame), a grabbing mechanism was developed. This device consisted of a comb-like arrangement of square nylon spikes mounted on an aluminum base. Molded carbon fiber strips were then attached between the nylon spikes to act as one-way latches that were designed to grab on to the PVC frame when the Sub descended to engage the frame. Once engaged and captured, the two carbon fiber latches overlap, thus preventing the release of the PVC frame. (See bottom right of Figure 1.)

3. Electronic Hardware

3.1 Batteries

SubjuGator uses eight MaxAmps lithium polymer battery packs; four 14.8V, 10Ah in parallel, and four 14.8V, 4Ah in series. Electronics, the embedded computers, and sensors run on the parallel configuration. The series configuration is dedicated to the thrusters. Lithium polymer chemistry batteries are preferable over other battery chemistries because of their high energy density and lower cell count. 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 electronics power source. The absolute worst case runtime is estimated to be 4 hours.

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: 2 Intel T7600 Core 2 Duo 2.33GHz CPUs, 2GB of 533MHz DDR2 RAM, and a 16GB SSD hard disk. This hardware runs the Microsoft Windows Server 2003.

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.

These computers are also the central point of our vehicle's sensor information and control system. Microsoft Robotics Studio (MSRS) is installed on the two nodes and coordinate 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 computers. By utilizing four FTDI FT232D Dual UARTs interfaced directly to an embedded 4-port USB hub, our computers 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 computers tremendously.

This board also directly hosts three important environmental monitoring sensors that continuously sample statistics such as temperature, pressure, and humidity. These sensors are the SHT15 humidity sensor from Sensirion and the SCP1000 pressure sensor from VTI.

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 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.

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 6Hz sample rate to the SubjuGator's main computer.

The Teledyne RD Instruments Explorer DVL (see Figure 4) 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 4 - Doppler Velocity Log Transducer

3.3.2 Digital Compass

SubjuGator uses a TCM5 compass (see Figure 5) 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.

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.

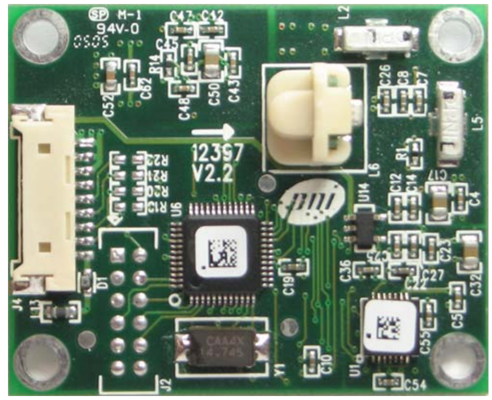

Figure 5 - TCM5 Compass

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 SSP-1 has a maximum output of 16 Hz.

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.

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. 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. The final task requires submarines to surface in one of two 9' diameter octagonal surface zones. While there are two surface zones, containing the safe, 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 (see Figure 6) 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 6 - 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 (see Figure 7). 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 7- 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.

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 (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.)

Figure 8 - Testing and Tuning Motor Control

In order to properly control the thrusters, a thruster calibration device was designed to measure voltage thrust curves. Each thruster has its own unique voltage curve available in software to simplify the control algorithm. The testing device was constructed to measure static thrust and involved a vertical lever arm and a thruster mount located on the bottom of the arm. A load cell was fixed in place, contacting the upper portion of the lever, so that when the thruster was activated, the arm transferred force from the thruster to the load cell. The load cell was detachable and had mounts on either side of the arm so that both the forward and reverse thrust characteristics could be measured. The thruster and lower arm were submerged in a tank of water so that the rest of the apparatus was fixed to the tank above the surface. Curve data was collected by applying a range of voltages to the thrusters while monitoring current and thrust. The load cell was calibrated with standard weights and scaled appropriately to account for the force multiplication by the lever.

4.3 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 kth 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 safe 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

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