SubjuGator 2003

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Abstract

Graduate and undergraduate students at the University of Florida are in the process of modifying and testing an autonomous submarine, SubjuGator, to compete in the 2003 AUVSI/ONR Underwater Vehicle Competition. SubjuGator is designed to operate underwater at depths up to 100 feet. Its motor orientations can be configured to optimize for mobility or speed. SubjuGator's body has mounts to support up to ten motors, each of which may be oriented in a multitude of directions. SubjuGator is controlled through a single-board Pentium3 based computer running the Linux operating system, which is interfaced to the motors through a microcontroller and to the camera through an IEEE1394 connection. On-board sensors include a digital compass, a fluidic inclinometer, a pressure sensor, and a sonar altimeter. Additionally, mission specific sensors include a high-resolution progressive scan camera and hydrophone system. In this paper, we first describe the mechanical construction of SubjuGator, including the mechanism used to deliver markers to the active target. Next, we describe the electronic and processing hardware as well as the motivation for our electronic design. We then discuss the various on-board sensors and mechanisms, both mission-dependent as well as mission-independent. Finally, we comment on vehicle control strategies and how we expect a typical competition run to proceed using the subsystems onboard SubjuGator to meet the mission goals.

1. Introduction

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) are sponsoring the Sixth Annual International Autonomous Underwater Vehicle Competition to be held in San Diego, California at the SPAWAR facility August 7th through 10th. A student team at the University of Florida is once again developing an AUV for this latest contest. SubjuGator has been revised and redesigned to meet the challenges of this year's competition.

To successfully complete this year's competition objectives, submarines must be able to differentiate an active arrow, designated by lit LEDs, from a set of three arrows situated on the floor of an underwater arena. They must then follow the approximate direction of the active arrow and sounds emitted by the pinger corresponding to the active target. Finally, the submarine must deposit a marker onto the target, which consists of three tiered trays of decreasing size with an LED in the center of the smallest, topmost tray. Points are awarded for successfully passing through a starting gate, for depositing markers on the target, and for the time taken to complete the given tasks.

In this paper, we first describe the mechanical construction of SubjuGator, including the mechanism used to deliver markers to the active target. Next, we describe the electronic and processing hardware as well as the motivation for our electronic design. We then discuss the various on-board sensors and mechanisms, both mission-dependent as well as mission-independent. Finally, we comment on vehicle control strategies and how we expect a typical competition run to proceed using the subsystems onboard SubjuGator to meet the mission goals.

2. Mechanical System

As a third-generation vehicle, SubjuGator embodies the lessons learned in six years of autonomous underwater vehicle (AUV) development. We considered several key design criteria, including the vehicle's hydrodynamics, its survivability in a salt-water environment, and its adaptability for different missions through easy motor reconfiguration and future sensor additions.

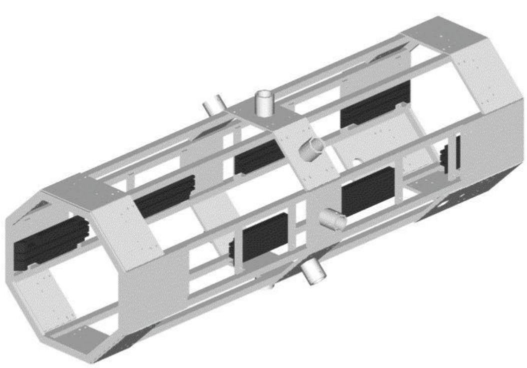

Figure 1: Body

2.1 Body

The 36" long octagonal shape is composed of 0.25" thick aluminum plate and 0.5" thick square bar. A bulkhead on each end fastened with quick-release latches keeps the internals dry, while allowing access to the components from either end of the submarine. Three hard-point rings are welded onto the frame (Figure 1) to strengthen the structure, provide mounting points for exterior sensors via blind-tapped holes, and carry all through-hull connections. The central hard-point ring also contains the cylindrical mounts for eight motors. The mount allows the motor's thrust to be positioned in line with the body, or perpendicular to it. With a mount on each of the eight faces of the submarine, a multitude of motor configurations are possible, allowing the vehicle to be adapted and optimized for a particular situation or mission. Figure 2 shows one configuration (a) optimized for mobility while the other (b) is optimized for speed and power. For the 2003 competition, we have chosen configuration (a) to maximize maneuverability.

2.2 Farings

The fore and aft flooded 14" farings provide a more streamlined flow around the vertical motors and the frame. Additionally, the farings offer structural support and protection

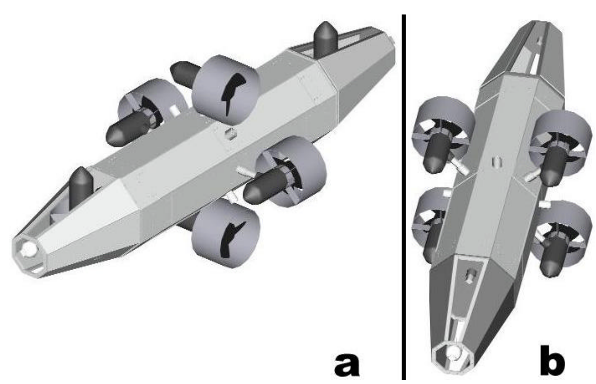

Figure 2: Example Configurations

to any sensor mounted within them. Both farings are open on the top and bottom to provide for upward or downward looking sensors. Moreover, the forward section of the frontal cone is open for any forward-looking sensors.

2.3 Motors

All six motors are Motorguide Power Plus electric trolling motors with 6.75" diameter propellers. At 12V these motors provide approximately 22 pounds of thrust, and are fitted with custom O-ring seals that allow for a salt-water depth of up to 100 feet. Each motor is shrouded to prevent incidental blade contact.

2.4 Through-hull connections

All through-hull connections use Burton 5500 series sealed and molded underwater connectors. A kill switch is implemented with a Gianni hermetically sealed push-pull switch that disconnects power from the motors and initiates a software motor kill routine. A power switch is implemented with a Gianni hermetically sealed SPST switch.

2.5 Interior layout

Two shelves guided on delrin rails provide support for all the internal electronics and power. Batteries and high-power electronics are stowed in the lower shelf to provide a metacentric righting-moment, while the upper shelf houses the remaining electronics. Electrical connections terminate at connectors at the front of the submarine for efficient removal of both shelves.

2.6 Exterior components enclosure

SubjuGator uses a custom built underwater vision system. To contain the camera and its connecting electronics, we have constructed an external downward mounted camera enclosure. This enclosure is mounted on the front nose of the submarine nominally pitched at 0 degrees forward, but is reconfigurable between zero and 40 degrees. It is constructed from a PVC compression fitting using a glass plate at one end, and a hose fitting at the other. The enclosure is connected to the internal cavity of the submarine, and therefore of equal pressure.

This year, the enclosure was expanded using a PVC T-connector and hoses to connect a structure containing the amplifier circuitry for the hydrophones. The amplifier structure is constructed of the same materials as the camera structure and mounted on the front of the vehicle with a second watertight tube running wires between the amplifiers and the hydrophones.

For extreme depths and testing purposes the submarine's internal cavity can be pressurized using a compressor and tubing attached to the camera enclosure connection. Equalizing pressure at extreme depths reduces the pressure gradient on the submarine, and, thus, the chance of hull failure. Pressurizing the cavity has also assisted us in finding microfractures in the outer casing of the submersible.

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 are steel balls with a diameter of 1.500 ± .002 in. A spherical ball was chosen for its aerodynamics structure, enabling it to descend quickly with as little drag and drift as possible.

The dropping mechanism, shown in Figure 3, is mounted externally on the ventral side near the frontal cone of the submarine. The mechanism is actuated through SubjuGator's aluminum hull wall by an electromagnet that attracts a rectangular piece of steel. The electromagnet is discussed further in section 3.5. Throughout the mission, the mechanism carries the markers within a holding tube, made of PVC pipe. When the target is detected, the electromagnet is activated, attracting the steel on the mechanism arm and pulling a pin that allows a trap door to open and the markers to fall onto the target.

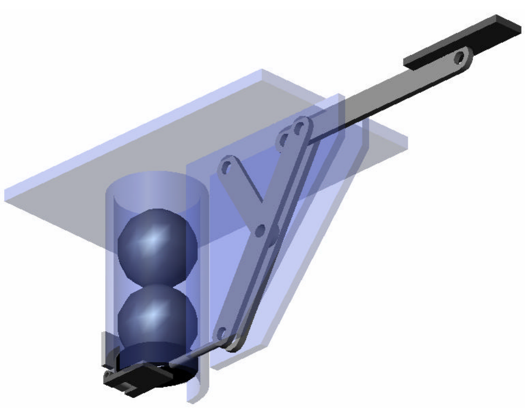

Figure 3: Dropping Mechanism

The mechanism is a four bar Hoeken-type linkage, as shown in Figure 4. This type of linkage was chosen in order to achieve optimum straight-line movement on any point of the coupler, allowing the pin holding the trap door to be removed in a straight line.

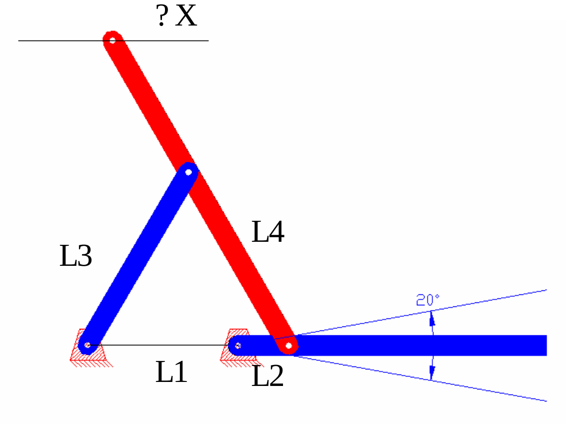

Figure 4: Hoeken Four Bar Mechanism

This mechanism was selected for its simplicity and because it creates straight-line motion. Designing for a starting angle of 170 degrees and a range of 20 degrees, the following ratio must be true in order to achieve a straight line:

$$\frac{L1}{L2} = 2.975; \frac{L3}{L2} = 3.963; \frac{\Delta X}{L2} = 0.601$$

Finally, due to a design requirement that L3 must be 2.5 inches long, the following linkage lengths were computed:

L1 = 1.8767
L2 = 0.6308

3. Electrical System

The electrical system of the submarine is composed of a power system (batteries and motor drivers), computing resources (x86 processor, microcontroller), sensors that provide information about the environment to the vehicle, and a circuit to control and power the electromagnet used to actuate the marker dropping mechanism, discussed in section 2.7.

3.1 Power supply

SubjuGator uses five Powersonic 12 Amp-Hour 12V sealed lead-acid batteries — three to power the motors, one to power the electronics, and one to augment the voltage supplied to the electromagnet. A Keypower DX250H DC-DC ATX power supply provides for all of the electronics contained within the submarine. This configuration allows for 2.5 to 3 hours of operational runtime.

3.2 Computing

The various tasks of the computing system on SubjuGator demand different approaches.

First, the vision system and the main intelligence require a powerful processor to perform real-time decision making and analyze the incoming sensor data. Second, the motor system requires a consistent and dependable output to control motor speed. To service these systems we chose the EEPD Pentium3 700MHz Envader embedded single-board computer, and the Motorola 68HC11 microcontroller.

3.2.1 68HC11

The Motorola 68HC11 is an eight-bit microcontroller unit with flexible and powerful on-chip peripheral capabilities. These include an eight-channel analog-to-digital (A/D) converter with eight bits of resolution, an asynchronous serial communications interface (SCI), and five output-compare timing output lines [5]. The A/D converter, together with the SCI system, interfaces analog sensors to the main processor. The SCI system also receives motor output specifications, which are fed to the output-compare lines to generate precise speed control (PWM) for the motors. These signals are then fed into motor driver boards, designed in house, to provide accurate high-current motor control.

3.2.2 Main processor

Top-level control is handled by an EEPD Envader single board computer. This Pentium3-based 700MHz board has 256MB of RAM, 20GB hard drive, IEEE1394 (Firewire), USB, PC/104+, and runs Red Hat Linux 9.0 [2]. We are using a PCMCIA adapter to interface our wireless Ethernet card. All sensor information, gathered on one system, is evaluated, and consequent instructions are then issued to all subsystems.

3.2.3 Wireless system access

A communications interface between a base station and the vehicle utilizes a wireless Ethernet (802.11b) connection with an 11Mb/s datapath. We are using ZoomAir 4105 cards. This allows secure shell, ftp, and simultaneous programmer access for parallel code development and debugging.

Testing of the submarine is performed by remote operation through software running across the wireless link. By viewing the real-time sensor data, we can tune most aspects of the submarine's intelligence and control.

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, sensors allowing for such control are present on almost all AUVs. We define these as navigational sensors.

3.3.1 Digital compass

SubjuGator uses a TCM2-50 compass from Precision Navigation. With a triaxial magnetometer, a fluidic inclinometer, and a microprocessor, this compass generates heading, tilt and roll information throughout its operational range. This sensor interfaces with a serial port on the EEPD.

3.3.2 Depth sensor

Depth measurements are gathered with a Measurement Specialties MSP-320 series pressure sensor. It is rated to 25 PSI with a rated accuracy of $\pm .25$ PSI and outputs an analog voltage between 1 and 5 volts, which translates to a depth resolution of ± 2 inches. This sensor interfaces with a A/D converter on the 68HC11.

3.3.3 Sonar altimeter

We acquire height measurements with respect to the floor of the pool with a Datasonics PSA-916 sonar altimeter. Our model is modified to measure distances from 30cm to 100m with a resolution of 1cm over an RS-232 connection. This sensor interfaces with a serial port on the EEPD.

3.4 Mission-specific sensors

This year's competition requires that the submersible locates a decision point consisting of three arrows. It must then select and calculate the orientation of the active arrow, designated by lit LEDs. Using the calculated orientation, the submarine must seek out the corresponding target by following a signal transmitted by that target's pinger. When the submarine arrives at the active target, it must deposit a marker onto one of the target's trays to complete the mission. We have two primary sensor systems that will be used to complete this mission. The first is a vision system, used to recognize the decision point and targets. The second is a hydrophone system, used to track and follow the transmissions emitted by the target pingers.

3.4.1 Underwater vision system

To accomplish underwater computer vision we have developed and constructed both hardware and software capable of capturing images and processing them completely onboard the submarine. We are using a Unibrain Fire-i400 progressive-scan camera, capable of 640x480 resolution at 15fps. This camera has an interchangeable lens and interfaces to our embedded computer through IEEE1394 (Firewire). The camera is mounted in an exterior enclosure, as described in section 2.6.

The latest Linux kernels have built in support for plug-and-play Firewire devices. Using the digital camera libraries available for Linux we have written custom software for both frame grabbing and acquiring video.

Using our camera and computer vision algorithms [6], SubjuGator is able to accomplish the detection, localization, and classification of the underwater targets and the decision point used for this competition. The computer vision code assumes a background intensity of Gaussian distribution, an assumption that was confirmed to be a valid after analyzing pictures of the arena from last year's competition. At the beginning of each run the submarine takes a sample mean and variance, which is used as the basis for its image processing calculations. Any pixels outside of the upper bound of the 95% confidence interval are assumed to belong to an LED. At the decision point this information is used to determine the vector between the LED array and the LED at the tip of the active arrow. The calculated vector is then compared to known headings of targets and the target with the closest heading is selected.

To verify that the "lights" detected by the submarine are indeed decision point LEDs, SubjuGator looks for rectangular objects in the area. This is accomplished by first passing the image through a Gaussian filter. Next, the Sobel operator is convolved with the image to detect edges. The horizontal segment lengths between detected edges are then measured. A ratio of the segment lengths and the mean segment length for that object are calculated and used as the feature vector for histogram based modeling. Finally, the log-likelihood of the object being a rectangle is computed. If the rectangle is present between the LEDs, the submarine has confirmed its detection of the decision point LEDs and begins to seek the target.

Similar techniques are used to detect the target LED and target boxes.

3.4.2 Hydrophone System

The hydrophone system consists of four basic stages that aid in obtaining and processing the signals transmitted by a target's pingers. These stages are:

1. Hydrophones
2. Amplifier
3. Embedded Signal Occurrence Identifier (ESOI)
4. ATMEGA8 microcontroller

The hydrophones provide a means with which to detect acoustic vibrations in the water, such as the signals transmitted by the pingers corresponding to each target. Figure 5 describes the processing of the hydrophone data. SubjuGator utilizes three hydrophones mounted in a triangle configuration to create the geometry needed to identify the direction from which the received signals originated. When the hydrophones detect a transmission from a pinger, they are only capable of producing a signal ranging from 50 mVp-p to 200 mVp-p, depending on the strength of the pinger's signal.

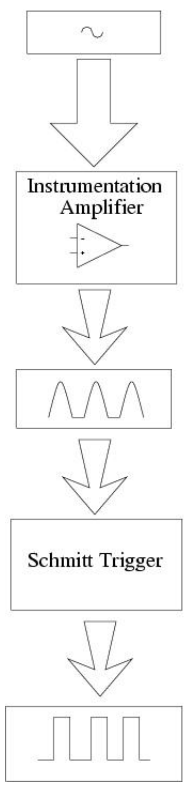

Figure 5: Hydrophone Signal Processing

Because of their weak signal strength, the three hydrophone outputs are fed directly into an amplifier circuit, consisting of Burr-Brown INA331 Instrumentation Amplifiers, where the signal is amplified by a gain of approximately 100. The amplifier output is then passed into a Motorola MC14583B Schmitt trigger to create the square wave necessary to trigger logic levels in the ESOI. The resulting three square waves are then passed on to the ESOI for further processing.

The ESOI system, consisting of a MAX7128S CPLD, takes the three digitized signals and judges whether or not they are the signals of interest. If they are, the system sends time of occurrence information to the ATMEGA8 microcontroller, otherwise it waits for the correct frequency to occur.

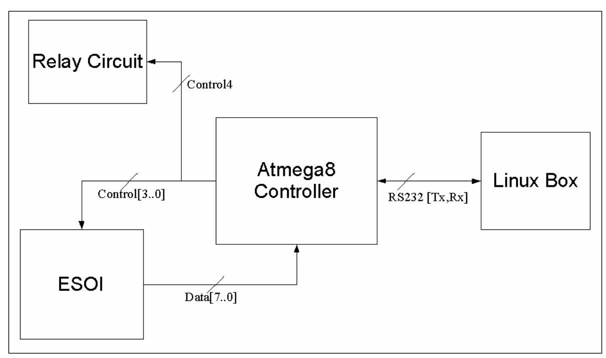

Figure 6: ATMEGA8 Connections

The ESOI system is under direct control of the ATMEGA8 microcontroller. The ATMEGA8 interface controller provides an RS232 interrupt driven state machine, which controls the ESOI logic as well as the electromagnetic relay circuitry, as shown in Figure 6. The microcontroller is in constant communication with SubjuGator's main computer system. The computer system tells the microcontroller which signals it needs to find as well as when to activate the dropping mechanism using the four following commands:

1. Request Frequency 1 Data
2. Request Frequency 2 Data
3. Request Frequency 3 Data
4. Drop Marker

The microcontroller receives these commands through the RS232 serial interface and sets the control lines of the ESOI system to the corresponding value. When the ESOI system finds the corresponding frequency, the microcontroller sends the information back to the main computer board for processing. This information will be used to triangulate pinger position.

In processing the information from the ATMEGA8 microcontroller, the computer system assumes a linear wave front over short distances. Using this assumption, as shown in Figure 7, we can conclude that the signal ripples striking two hydrophones, at t1 and t2, are parallel to each other. Applying simple geometry principles we can create a right

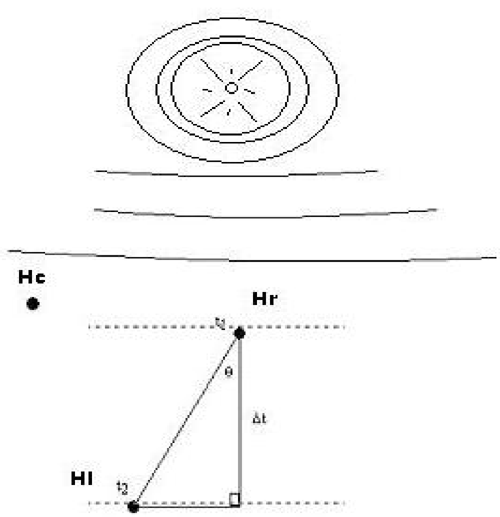

Figure 7: Hydrophone Signal Geometry

triangle whose hypotenuse is 5.08cm, due to our hydrophone mounting configuration. The length of the triangle leg adjacent to theta is proportional to Δt = t1 - t2. Knowing that signals travel underwater with a velocity of 1450m/s we can calculate the length of the adjacent leg:

$$L_{adj} = \frac{\Delta t}{f_{clk}},$$

where f_{clk} is the clock frequency of the free running counter in the input capture system, which is 4 MHz in our system.

The ultimate goal of our system is to orient the submarine to the heading of the active target's pinger. This is accomplished using control strategies, discussed in section 4, to rotate until the angle theta is equal to 90 degrees using the following equations:

$$\cos(\Theta) = \frac{L_{adj}}{5.08\text{cm}} \qquad \Theta = \arccos(\frac{L_{adj}}{5.08\text{cm}}).$$

3.5 Electromagnet & Relay Circuit

A large electromagnet is mounted within the submarine, flush against the ventral hull wall. The purpose of the electromagnet is to attract a rectangular piece of steel, actuating the marker dropping mechanism and releasing the markers onto the target. The dropping mechanism and markers are discussed in section 2.7.

Selecting an electromagnet to actuate the dropping mechanism enabled us to activate the externally mounted marker dropping mechanism through SubjuGator's aluminum hull without drilling a hole in the submarine. The advantage of this system is that we neither had to structurally compromise the hull nor deal with waterproofing holes or tubes connecting the system to the outside. The disadvantage is the large amount of electromagnetic interference caused by the activation of such a large magnet. To minimize such effects, a case of magnetic shielding has been constructed around the electromagnet.

The electromagnet is triggered by a simple relay circuit. When the circuit receives a 5 Volt signal from the ATMEGA8 interface controller, the signal activates a transistor, which switches the relay and allows current to flow through the electromagnet. The electromagnet in turn actuates the dropping mechanism, as shown in Figure 3, to drop the markers onto the target.

4. Vehicle control and strategy

4.1 PID controller

As the submarine moves through the water, errors between the desired and current values of heading, pitch, and depth are controlled through a standard PID controller. The determination of the motor actuation values is based on the submarine's position and orientation divergence. The continuous equation is converted to its discrete-time equivalent and the errors are calculated from the difference between the current and desired heading, pitch, and depth [3,5],

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

In the above equation, $m(t)$ represents the motor value and $e(t)$ represents the error at time step t. The individual gains (Ki) are tuned through repetitive testing at various depths and operating conditions. For each of our possible speed and depth range configurations, we maintain a separate set of control parameters. These parameters are determined through experimentation and simulation. We also use a PID controller to maintain the vehicle's pitch.

4.2 Arbiter

Each of the sensor analysis processes makes heading, speed, and/or depth requests to improve the position of the submarine in relation to the targets. Due to the various strengths and weaknesses of particular sensors, and the occasional sensor anomaly, these requests may sometimes conflict. Therefore, we have implemented an arbiter, a rule-based algorithm specifically tuned for the competition environment, which is tasked with deciding on the next action for the submarine, given the various, possibly erroneous, sensor inputs.

Our solution to locating the correct target and delivering our markers to the target will logically proceed as follows: The submarine will dive to a pre-determined depth and travel through the validation gate. It will continue on its course until the camera system and vision code recognize the decision point. Here, the computer vision system will locate the active arrow, calculate the approximate vector based on the active LEDs, and match the vector to the corresponding target. The hydrophone system will then tune itself to the frequency of the active target and the submarine will travel towards the signal until the target is located by the vision system. At this point, the computer vision system will be used to align the submarine with the target and the electromagnet will be activated, actuating the dropping mechanism and dropping two markers on the target. More details of our solution will be divulged during SubjuGator's competition run.

5. Acknowledgements

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