SubjuGator 2004

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Abstract

Graduate and undergraduate students at the University of Florida are in the process of creating an autonomous submarine, SubjuGator, to compete in the 2004 AUVSI/ ONR Underwater Vehicle Competition. SubjuGator is designed to operate underwater at depths up to 16 feet. Its motor orientations are configured to maximize mobility. 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 cameras through an IEEE1394 connection. Onboard sensors include a digital compass, a fluidic inclinometer, and a pressure sensor. Additionally, mission specific sensors include two high-resolution cameras 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 onboard 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 Seventh Annual International Autonomous Underwater Vehicle Competition to be held in San Diego, California at the SPAWAR facility July 29th through August 1st. A student team at the University of Florida is once again developing an AUV for this latest contest. SubjuGator has been redesigned to meet the challenges of this year's competition.

To successfully complete this year's competition objectives, submarines must be able to <perform a task>. 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.

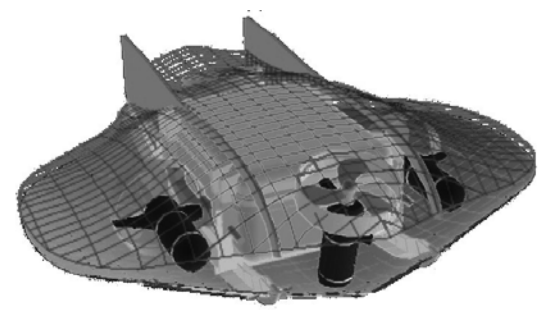
2. Mechanical System

As a fourth-generation vehicle, SubjuGator embodies the lessons learned in seven 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.

For the 2004 competition, the Machine Intelligence Lab is venturing down a path few are willing to trek. Keying off the graceful and articulate lines of a stingray, the University of Florida's design goes beyond the traditional submarine technology. Preconceived notions have been shed to take advantage of rules that stipulate the submarine must fit within a 3'x 3'x 6' box and weigh less than half of last year's vehicle weight. New weight requirements were also considered in the new design. Blending composite materials with a wet hull design, team members are aiming for a compact package that weighs less than seventy pounds.

2.1 Body

The central core of the body is a 16" by 12" Pelican waterproof case. This was chosen because it gave us a cheap, quick, and – most importantly – lightweight housing. This box contains all the electronics we will be carrying. To support the motors and other external features we welded a frame made out of .125" thick aluminum angle iron. Two motors are positioned in line with the body propelling the thrust out the back. Two other motors are positioned perpendicular to the body forcing water upward to accomplish the downward force needed to submerse a submarine. Obviously – when needed – each motor can output in the opposite direction as well. None of this beautiful framework will be seen by the public. Encompassing the whole structure is a shell constructed that combines fiberglass and carbon fiber with an epoxy resin. Science fiction fans of the 1960's may recognize the new design as it is founded on the *Flying Sub* from the television series *Voyage to the Bottom of the Sea*. As today's cell phones mimic the communicator in *Star Trek*, UF is opening new areas of research for tomorrows' submarine. As shown below, three-dimensional Computer Aided Design models have been created and given enough time, fluid dynamic tests could be simulated. The design is moving forward based predominantly on experience and educated guesses.



2.3 Motors

All four motors are Sevylor electric trolling motors with 6.75" diameter propellers. The props are aftermarket, 2-blade Minn-Kota models in order to give us more thrust in both directions. At 12V these motors provide approximately 13 pounds of thrust. These motors are smaller then what we have used in the past because we wanted to minimize the overall weight of the sub – each one weighs only 4 pounds. For safety each motor is shrouded to prevent incidental blade contact.

2.4 Through-hull connections

All through-hull connections use Subconn Micro Bulkhead series wet mateable 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.

2.5 Interior layout

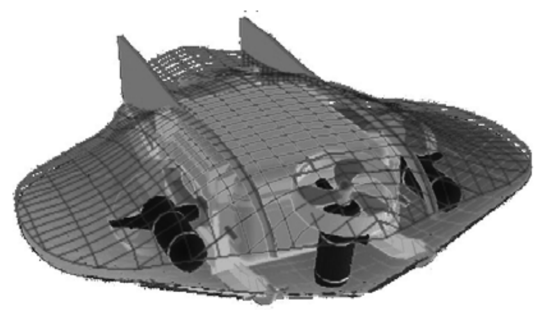
Two shelves guided on delrin rails provide support for all the internal electronics and power. Batteries and high-power electronics are stowed in the lower shelf to provide a metacentric righting-moment, while the upper shelf houses the remaining electronics. Electrical connections terminate at connectors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



mersible.

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.

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.

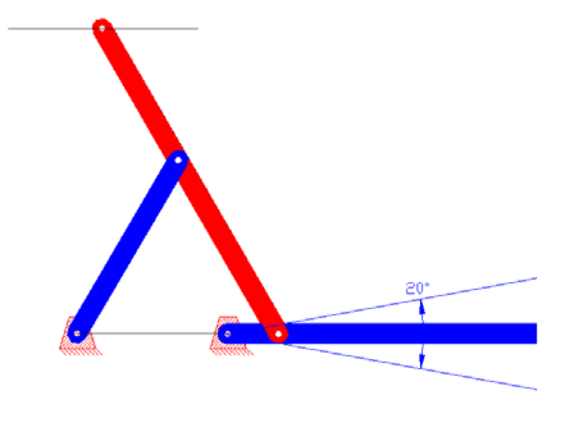
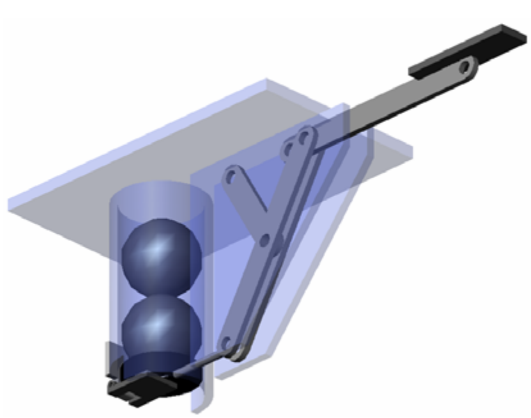


Figure 4: Hoeken Four Bar Mechanism

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:

$$\frac{L1}{L2}=2.975;\ \frac{L3}{L2}=3.963;\ \frac{\Delta X}{L2}=0.60$$

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



ΔX

L4

L3 **Figure 3: Dropping Mechanism**

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 solenoid used to actuate the marker dropping mechanism, discussed in section 2.7.

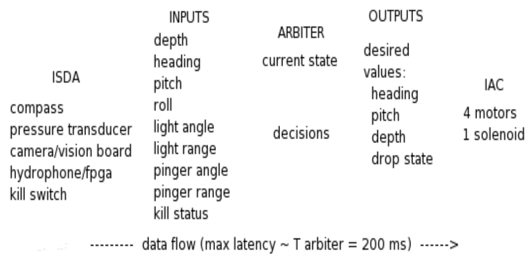
3.1 Power supply

SubjuGator uses two Powersonic 7 Amp-Hour 12V sealed lead-acid batteries to power the motors. Three Kokam Lithium-Polymer 3720 mAh cells power the electronics at 11.1 volts nominal. A DC-DC ATX power supply provides for all of the electronics contained within the submarine. This configuration allows for approximately one hour of operational runtime.

3.2 Computing

The various tasks of the computing system on SubjuGator demand different approaches. The vision system requires a powerful processor to perform real-time scene analysis. Thus, an EEPD Pentium3 700MHz Envader embedded single-board computer is provided for onboard processing. The subsystems and sensors of the AUV are integrated using an Atmel Atmega128. The microcontroller makes mission and higher level decisions along with controlling analog and timing related interfaces.

3.2.1 Atmel



The Atmel ATmega128 is an eight-bit microcontroller unit with flexible and powerful on-chip peripheral capabilities. The functionality of this microcontroller include an eight-channel analog-to-digital converter (ADC) with ten bits of resolution, two universal asynchronous serial transever (UART), and eight high-precision timing output lines. The architecture of the code onboard the Atmel is designed as an interrupt-driven sensor data acquision (ISDA) and interrupt-driven accutuator control (IAC). The incorporation of the ISDA/IAC philosophy eliminates wasteful polling routines freeing processor time to make high level decisions and perform complex calculations.

All subsystems are integrated on board the Atmel. The only sensors not integrated directly are the cameras and the hydrophones (which require preprocessing to obtain the desired information). The PWM (output) signals are then fed into motor driver boards, designed in house, to provide accurate motor control.

3.2.2 Altera FPGA

An Altera Flex 10K70 serves as a flexible hardware expansion device. Currently, logic cells are utilized for debug registers, additional I/O pins, and hydrophone logic. For further information on the hydrophones, reference section 3.4.2.

3.2.3 Image processor

Image processing is handled by an EEPD Envader single board computer. This Pentium3-based 700MHz board has 512MB of RAM, 20GB hard drive, IEEE1394 (Firewire), USB, PC/104+, and runs Slackware 9.1 [2]. We are using a PCMCIA adapter to interface our wireless Ethernet card. In addition, a serial link is used to communicate with the Atmel.

3.2.4 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 Atmel microcontroller.

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 +/- .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 Atmel microcontroller.

3.4 Mission-specific sensors

This year's competition requires that the submersible navigates toward a light source. It must then deposit its markers on one of the targets located in front of the light source. After launching its markers the submersible mut then navigate towards a pinger that is located in the "Recovery Zone". Once the vehicle arrives to the "Recovery Zone", it must surface to end its run. We have two primary sensor systems that will be used to complete this mission. The first is a vision system, used to recognize the light source and targets. The second is a hydrophone system, used to track and follow the transmissions emitted by the "Recovery Zone" 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 30fps. This camera has an interchangeable lens and interfaces to our embedded computer through IEEE1394 (Firewire). The camera is mounted internally. Forward vision is handled by an Apple iSight camera, daisy-chained on the Firewire bus. The camera is mounted externally, 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 light source 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.

To verify that the "lights" detected by the submarine are indeed the light source 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 light source. Similar techniques are used to detect the targets.

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:

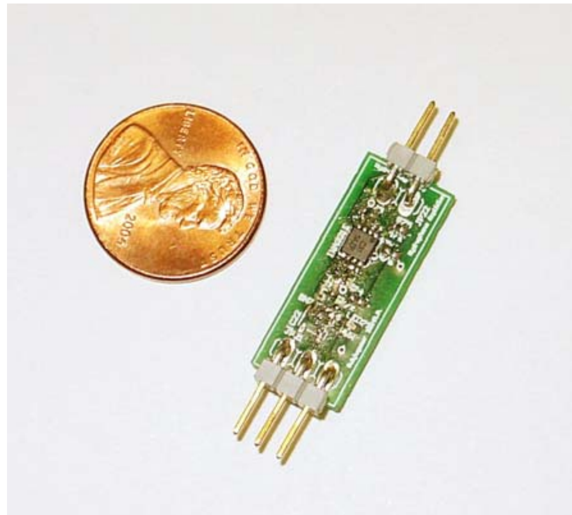
1. Hydrophones
2. Amplifier
3. Embedded Signal Occurrence Identifier (ESOI)
4. ATMEGA128 microcontroller

The hydrophones provide a means with which to detect acoustic vibrations in the water, such as the signals transmitted by the pingers corresponding to the recovery zone. 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.

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 SN74LVC1G17 Single 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 FPGA for further processing.

The FPGA, 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 ATMEGA128 microcontroller, otherwise it waits for the correct frequency to occur.

The ESOI system is under direct control of the ATMEGA128 microcontroller. The ATMEGA8 interface controller provides an RS232 interrupt driven state machine, which controls the ESOI logic as well as the solenoid relay circuitry, as shown in Figure 6.



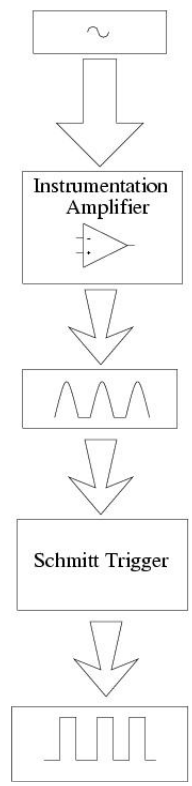


Figure 5: Hydrophone Signal Processing

The microcontroller receives these commands through a memory mapped register and sets the control lines of the ESOI system to the corresponding value. When the ESOI system finds the corresponding frequency, the microcontroller uses the information for processing. This information will be used to triangulate pinger position.

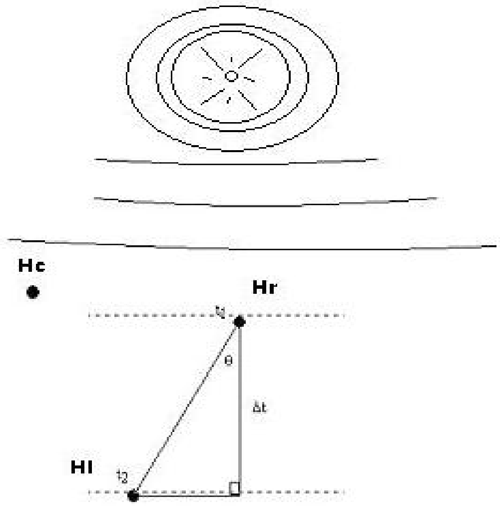


Figure 7: Hydrophone Signal Geometry

In processing the information, the ATMEGA128 microcontroller 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 triangle whose hypotenuse is 5.08cm, due to our hydrophone mounting configuration. The length of the triangle leg adjacent to theta is proportional to $\Delta t = t1 - t2$. 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:

$$\cos(\theta) = \frac{L_{a}}{5.0}$$

3.5 Electromagnet & Relay Circuit

A solenoid is mounted within the submarine, flush against the ventral hull wall. The purpose of the solenoid is to retract 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.

The solenoid is triggered by a simple relay circuit. When the circuit receives a 5 Volt signal from the ATMEGA128 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],

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

In the above equation, $m(t)$ represents the motor value and $e(t)$ represents the error at time step t. The individual gains (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.

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 following the light until the camera system and vision code recognize the drop bins. After dropping the markers, the hydrophone system will then tune itself to the frequency of the pinger and the submarine will travel towards the signal until the recovery zone is reached. The surfacing of the submarine will signify the end of our run

5. Acknowledgements

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