SubjuGator: Sinkin' is Easy

Jason Grzywna, Scott Kanowitz, Jennifer L. Laine, Scott Nortman, David K. Novick, Kevin Walchko
Michael C. Nechyba, Antonio Arroyo, Eric M. Schwartz

Machine Intelligence Laboratory
University of Florida
Gainesville, FL 32611

http://www.mil.ufl.edu/subjugator

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 2001 ONR/AUVSI Underwater Vehicle Competition. SubjuGator is designed for operation down to 100 feet, and can be quickly 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 any direction in its plane. SubjuGator is controlled through a single-board 586 computer running the Linux operating system, which is interfaced to the motors and sensors through two other processors, a DSP and a microcontroller. On-board sensors include a digital compass, a fluidic inclinometer, inertial measurement unit, and a pressure sensor. Additionally, mission specific sensors include a hydrophone array for acoustic ping detection and localization, a CdS array for visual strobe detection and localization and a sonar altimeter for height detection. In this paper, we first describe the mechanical makeup of SubjuGator. Next, we describe the electronic and processing hardware, and the motivation for our electronic design. We then discuss the various on-board sensors, both mission-dependent as well as mission-independent. Finally, we comment on vehicle control strategies.

1. Introduction

The Autonomous Unmanned Vehicle Systems international (AUVSI) and the Office of Naval Research (ONR) are sponsoring the Forth Annual Autonomous Underwater Vehicle competition to be held in Annapolis, MD, July 11-15, 2001. A student team at the University of Florida is once again developing an AUV for this latest contest. SubjuGator has been somewhat revised and redesigned to meet the challenges of this year's competition.

This year the submarine must navigate a pond by first passing through a validation gate and then searching for a target, marked by an acoustic pinger and visual strobe, located at the end of an array of boxes. Points are awarded for passing through the validation gate, determining the ping rate of the acoustic pulse, the flash rate of the visual strobe, the depth of the shallowest box in the array and returning to the dock with the marker.

In this paper, we first describe the mechanical makeup of SubjuGator. Next, we describe the electronic and processing hardware, and the motivation for our electronic design. We then discuss the various on-board sensors, both mission-dependent as well as mission-independent. Finally, we comment on how we expect a typical competition run to proceed and how the subsystems on board SubjuGator will allow us to meet the mission goals.

2. Mechanical System

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

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 sub. 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 sub, a multitude of motor configurations are possible, allowing the vehicle to be quickly 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 2001 competition, we have chosen configuration (a).

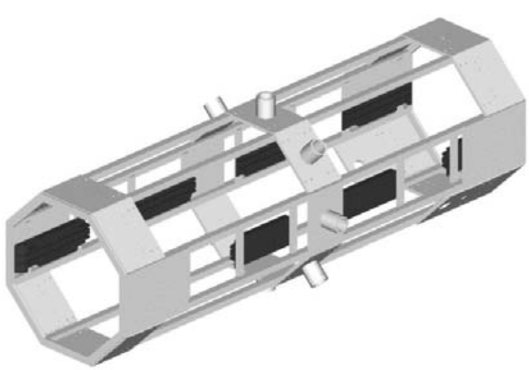

Fig 1. Body frame

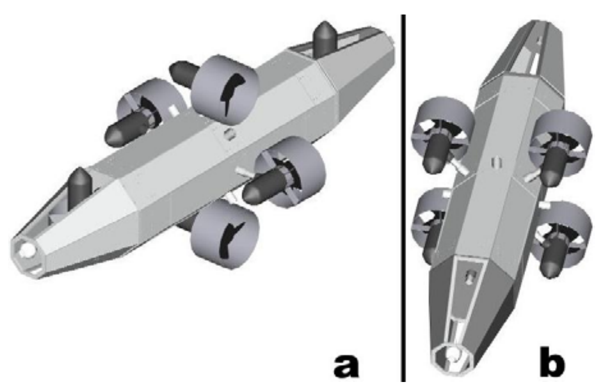

Fig 2. Example Configurations

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 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 fore 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 sub for expedient removal of both shelves.

2.6 Exterior electronics box

Both the passive acoustic localization system and the CdS strobe detector require sensitive devices that must be close to their respective driver circuitry. To overcome this sensor distance problem we have designed an exterior electronics box to house all the driver circuitry necessary for both detection systems. The box is mounted on the front underside of the body.

2.7 Marker retrieval device

A passive method for grabbing the marker was sought due to the added complexity of additional actuators. A configuration was chosen to resemble a comb. The width of the comb is 36”, maximizing its coverage. There are 21 “fingers”, 1.75” apart, which extend approximately 6.5” from the base of the assembly. Each “finger” of the comb has

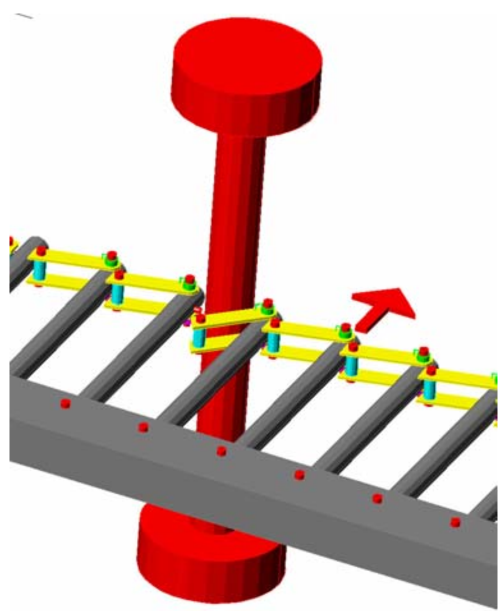

Fig 3. Marker retrieval device

a conical tip that minimizes drag and aids in grabbing the marker. Additionally, spring loaded, one-way latches prevent the marker from slipping out of the comb (Figure 3).

3. Electrical System

The electrical system of the vehicle is composed of a power system (batteries and motor drivers), computing resources (x86 processor, microcontroller and DSP) and the sensors that provide information about the environment to the vehicle.

3.1 Power supply

SubjuGator uses four Powersonic 12 Amp-Hour 12V sealed lead-acid batteries, three to power the motors, and a one to power the electronics. A Wall Industries DC-DC converter supplies 5V at 8A for the electronics. This configuration allows for 3 to 3.5 hours of operational runtime.

3.2 Computing

The various tasks of the computing system on SubjuGator demand different approaches. First, the motor system requires a consistent and dependable output to control motor speed. Second, the acoustic ping location system requires high-speed data acquisition, while the main intelligence simply requires a powerful processor. To service these systems we chose the Motorola 68HC11, the Motorola DSP56309 Digital Signal Processor, and the WinSystems LBC-586Plus embedded single-board computer, respectively.

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 lines. The A/D converter, together with the SCI system, interfaces analog sensors to the digital main processor. The SCI system also receives motor output specifications, which are fed to the output compare lines to generate exact speed control for the motors. These signals are then fed into motor driver boards we designed to provide precise high-current motor control.

3.2.2 Digital signal processor

The Motorola DSP56309 is an 80MHz 24-bit fully pipelined DSP. Of the many features of this system, the ones we are exploiting are (1) a serial communications interface, (2) system interrupt timer pins, and (3) a data acquisition time resolution of 27ns. The system interrupt timer pins extract phase information from the acoustic localization system to determine the bearing to the beacon. The SCI system receives instructions from the main processor, and transmits phase information to the main processor.

3.2.3 Main processor

Top-level control is handled by a WinSystems LBC-586Plus single-board computer with 32MB RAM, running Red Hat Linux. All sensor information, gathered on one system, is evaluated, and consequent instructions are then issued to all subsystems.

3.2.4 Wireless system access

A communications interface between a base station and the vehicle utilizes a wireless Ethernet (IEEE802.11) connection with a 1.2Mb/s datapath. This allows telnet, ftp, and simultaneous programmer access for parallel code development and debugging.

3.3 Navigational sensors

For even the most basic operation, an AUV must be able to maintain a heading, a depth and attitude. Sensors to allow this are present on almost all AUVs, regardless of any specific mission. We define these as navigational sensors.

3.3.1 Digital compass

SubjuGator uses a TCM2 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.

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.

3.3.3 Inertial Measurement Unit

Dead reckoning is performed using a solid-state vertical gyro (DMU_HDX) from Crossbow Technologies intended for airborne applications such as UAV control, Avionics, and Platform Stabilization. This high reliability, strap-down inertial subsystem provides pitch, roll, pitch rate, roll rate, yaw rate, and x-y-z accelerations with static and dynamic accuracy comparable to traditional spinning mass vertical gyros. Data is transmitted between the submarine and the DMU serially via an RS-232 connection.

3.4 Mission-specific sensors

The competition task requires the localization of a barbell shaped object and a series of crates located near a beacon emitting periodic acoustic and visual pulses. A secondary mission objective is to determine the period of the individual signals. Due to the dissimilar nature of the three "marking" methods, we have augmented the basic sensor suite to allow us to completely achieve the mission goals.

3.4.1 Sonar altimeter

We acquire height measurements with a Datasonics PSA-916 sonar altimeter. This model is modified to measure distances from 30cm to 100m with a resolution of 1cm over an RS-232 connection.

3.4.2 CdS strobe detector

We accomplish the detection, localization and frequency determination of the strobe light through a series of light sensors and specialized circuitry. The sensors are four cadmium-sulfide (CdS) photoresistors that react to light by changing electrical resistance. They are arranged around the front of the nose cone to effect forward-looking coverage of the water. Figure 4 indicates the coverage provided by the arrangement of four sensors on the front of the vehicle.
When designing the strobe detection hardware, environmental noise was a

major consideration. In particular, the circuitry must detect a single flash from the strobe in an environment with varying ambient light and possible reflections from the sun off the water. Since a flash is basically a high frequency signal, we designed the sensor and circuitry combination to reject changes in light with a frequency less then 30kHz, a frequency threshold, which we determined experimentally. The result is a calibration-free sensor that can detect and localize flashes in an environment where ambient lighting varies significantly.

To adjust the field of view of each sensor, the photoresistors are collimated using a variable-length shroud. The amount of collimation is based on the mission objectives and operating environment of the vehicle.

3.4.3 Passive acoustic localization

3.4.3.1 System overview

The acoustic localization system consists of a passive hydrophone array that is tuned to the frequency of the beacon.

Fig 4. CdS array

With each received acoustic pulse, the array is able to calculate the bearing to the pinger relative to the AUV. The system utilizes three major components: a three-element hydrophone array, signal-detection circuitry, and a digital signal processor (DSP). The system is able to calculate a direction vector to a sound source (in this case an acoustic pinger) by measuring the phase difference of the signal of interest between a set of hydrophones with a fixed geometry.

3.4.3.2 Hydrophone Array

Figure 5 illustrates the basic geometry of the hydrophone array. The hydrophone spacing is parameterized by *d*, the distance between the corner hydrophone, H0, and its two adjacent hydrophones H1, and H2. This creates a fixed relationship for the delay times between hydrophones on the same axis, which are exploited by the algorithm. It is very important for *d* to remain smaller than one-half of the wavelength of the measured signal to prevent aliasing on the output vector. The hydrophones are custom-designed International Transducers part ITC-4155A. They are onmidirectional in their horizontal plane, and their sensitivity at 27kHz is close to –203dBV referenced to 1μPa.

3.4.3.3 Signal-detection circuitry

To measure the phase difference between two signals, a distinguishable common point must be chosen so that the time delay measurements will be accurate. A convenient point is the negative-going zero-crossing of a sinusoid (Figure 6). We designed specialized circuitry to take care of extracting the exact zero-crossing time for each signal. We amplify and filter raw hydrophone data

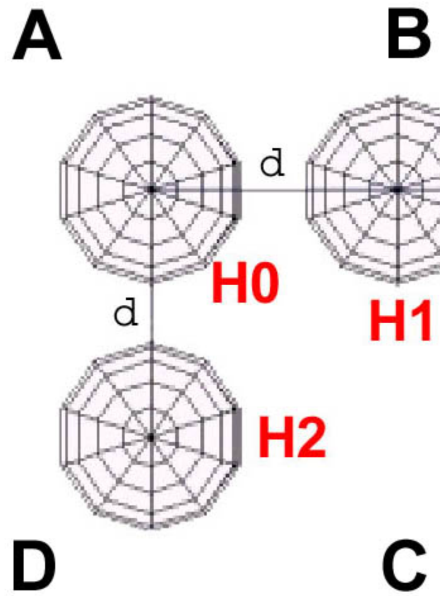

Fig 5. Hydrophone Array

before phase information can be extracted, as illustrated in Figure 7.

Given the beacon power output of 174dB re 1μPa, the hydrophone sensitivity of -203dBV re 1μPa, and neglecting attenuation due to the small size of the pond, the output of each hydrophone will be 0.05mV $_{p\text{-}p}$. An instrumentation amplifier with a gain of 20 will sufficiently amplify this voltage to a suitable level for filtering. The small scale of the hydrophone output stresses the importance of using high-quality instrumentation amplifiers that will reject common-mode noise and provide wide bandwidth. The amplifier is an Analog Devices AD623.

The wide-band amplified signal now passes through a fourth-order Chebyschev bandpass filter to eliminate out-of-band noise. The filter has a center frequency of 27kHz and bandwidth of 2kHz. A Maxim MAX268 provides a single-chip filtering solution. At the

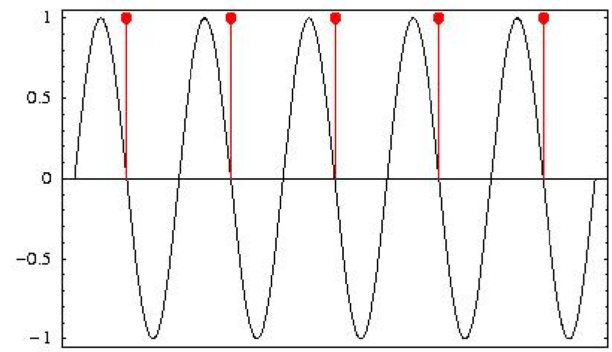

Fig 6. Zero-Crossing Detection

passband, the filter has a gain of 100, generating an output voltage large enough for zero-crossing detection. A National Semiconductor LM1815 variable reluctance sensor amplifier acts as a zero-crossing detector. It triggers only on signals greater than 200mV peak, rejecting almost all of the noise that is not sufficiently attenuated by the filter. The output is a quick (7 μs) voltage pulse, which is fed into the DSP for processing.

3.4.3.4 Digital signal processor

The signal-detection circuitry described above transforms the output of the hydrophones into periodic pulses representing the zero-crossing points of the acoustic signal from the beacon. Since these pulses are about 37 microseconds apart (one period of a 27kHz sinusoid), the measured phase difference (time between zero-crossing for two hydrophones) will range from 0 to 37μs. During each 5 millisecond pulse the DSP captures 128 data points (phase differ-

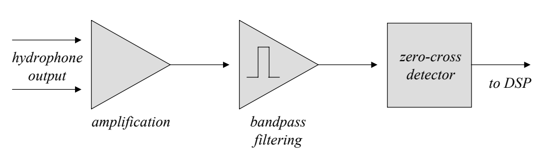

Fig 7. Signal detection

ence measurements) per hydrophone. This large number of samples helps to discard anomalous readings, and gives some measure of confidence for the direction vector (i.e., how many of the readings agree with each other).

3.4.3.5 Algorithm and output

Two datapoints corresponding to the time delays are input to the algorithm: t_1 and t_2 are the phase difference between H0 and H1, and H0 and H2 respectively. We break up the space around the array into octants with H0 at the origin, the H0 - H1 line on the *x*-axis and the H0 - H2 line on the *y*-axis. We shall further assume that signals will only be received from below the array (i.e., only signals with negative *z*-axis values), a sensible assumption since we know the beacon is at the bottom of the lake. This reduces the space into four "octants," which we label A, B, C and D as shown in Figure 5. Given these definitions there a four possible relationships between t_1 and t_2 depending on from which octant the signal originated. Table 1 shows these relationships where τ is the period of the 27kHz signal.

The octant is determined by comparing the measured values of t_1 and t_2 to the wavelength, τ. If the value of t_1 is less than one-half τ octants A and D are chosen otherwise octants B and C are chosen. The value of t_2 is then used to decide between A and D or B and C. If t_2 is less than one-half τ octant A or B is chosen, otherwise octant C or D is chosen [1].

Octant A	*Octant B*
$\theta_\alpha = \pi - \cos^{-1}(t_2 / t_d)$ $\theta_b = \pi - \cos^{-1}(t_1 / t_d)$	$\theta_\alpha = \pi - \cos^{-1}(t_2 / t_d)$ $\theta_b = \cos^{-1}((\tau - t_1) / t_d)$
Octant D	*Octant C*
$\theta_\alpha = \cos^{-1}((\tau - t_2) / t_d)$ $\theta_b = \pi - \cos^{-1}(t_1 / t_d)$	$\theta_\alpha = \cos^{-1}((\tau - t_2) / t_d)$ $\theta_b = \cos^{-1}((\tau - t_1) / t_d)$

Table 1. Octant angle relationships

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 will be controlled through a standard PID controller. The determination of the motor actuation values is based on the submarine's position and orientation divergence according to,

$$m(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \qquad (1)$$

where $m(t)$ is the motor value and $e(t)$ represents the error at time step t. 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.

4.2 Kalman filter

The Kalman filter is an alternative way to calculate the minimum mean-squared error (MMSE) using state space. R. E. Kalman, a graduate research professor in the Electrical Engineering Department of University of Florida, first developed the filter in 1960. Some of the advantages that the Kalman filter has over other estimators are: computational efficient by recursively processing noisy data, real-time estimator, can be adapted to non-stationary signals, handle complicated time-variable multiple-input/output systems, vector model random processes under consideration.

The Kalman filter estimates a process by using a form of feedback control. The filter estimates the process state at some point in time and then obtains feedback in the form of noisy measurements. The filter equations fall into two groups: time update equations and measurement update equations. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the a priori estimates for the next time step. The measurement update equations are responsible for incorporating a new measurement into the a priori estimate to obtain an improved a posteriori estimate. The time update equations can also be thought of as predictor equations, while the measurement update equations can be thought of as corrector equations [2].

4.3 Arbiter

Each of the sensor analysis processes make heading, speed and depth requests to improve the position of the sub in relation to the target. 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 sub, given the various, possibly erroneous, sensor inputs.

We describe a hypothetical successful mission run below. The sub will dive to a pre determined depth and align on the proper heading to the validation gate. The sub will then traverse the distance to the gate and stop when this distance has been reached. The hydrophone array will then derive the bearing to the marker and boxes. The sub will then traverse laterally to align itself in front of the marker, and search for the boxes. Once the heights of the five boxes and the frequency of the strobe is found, the target is retrieved and the sub turns and heads for the dock before surfacing.

5. Acknowledgements

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6. References

[1] US patent 4,622,657, "Acoustic Direction Finding Systems," Nov. 11, 1986.

[2] Rogers, R. M., Applied Mathematics in Integrated Navigation Systems, Reston, VA: American Institute of Aeronautics and Astronautics, 2000.