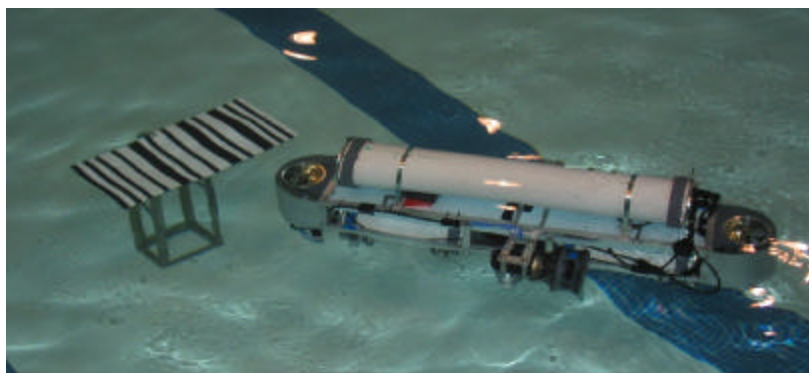# Cornell University Autonomous Underwater Vehicle Team

CUAUV

2002

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Abstract

CUAUV 2002 comprises Cornell University's entry into the 5th annual AUVSI International Autonomous Underwater Vehicle Competition. To meet the challenges presented by the 2002 competition rules and the SPAWAR TRANSDEC facility, this year's entry is equipped with a combination of systems successfully employed on previous vehicles as well as novel designs developed over the past year.

The 2002 Cornell AUV is 1.25 meters long, 0.5 meters wide, 0.4 meters tall, and displaces 50 kg. A pair of thrusters mounted port and starboard provides longitudinal propulsion and yaw control. An additional pair of 4-inch diameter thrusters located fore and aft control depth. A pack of sealed lead acid batteries provides 410 watts to the vehicle's sensing, processing, and propulsion systems. The AUV incorporates a Doppler Velocity Log (DVL) acoustic navigational system to improve vehicle control and augment navigational path planning. New Digital Signal Acquisition (DSA) modules will improve the vehicle's ability to detect and determine the bearing to the acoustic pinger, and a PC104+ frame-grabber interface allows for the capture and analysis of images gathered through an onboard camera. Controlling the aforementioned systems is a PC104+ form-factor PRO-FIVE C3VE Pentium III 700 MHz computer running Linux.

Introduction

The 5th International AUV competition is to be held July 31 through August 4, 2002, at the U.S. Navy's Transducer Evaluation Center (TRANSDEC) on the grounds of SPAWAR in San Diego, California. The goal of the competition is to conduct a bathymetric survey of an area populated with several man-made target objects and read the bar codes printed on them. The center of the target area will be marked with an acoustic pinger operating at 27 kHz.

Relying on this acoustic beacon as its primary source of navigational information, the Cornell University AUV will seek in a 20 minute operational period to successfully pass through a validation gate, locate the pinger, navigate the target areas while acoustically and visually searching for the bar-coded objects, and record for later retrieval the number and corresponding depth of each target encountered. The submarine will operate in a completely autonomous fashion while carrying out this mission, with all navigational and objective-sensing tasks performed by the vehicle's integrated sensing and computing suite.

In addition to new mission requirements for the 2002 IAUV competition, the acoustic trap feature of the TRANSDEC pond and hydrostatic pressure issues associated with a deeper water environment pose complex challenges to vehicle design, system development and strategy formulation. These new challenges have warranted innovative solutions that set the Cornell's 2002 AUV apart from previous entries.

Design Overview

Prior to designing any components for the vehicle, the Cornell team sought to assess the challenges presented by the TRANSDEC facility and brainstorm strategies to accomplish the mission of the 5th International AUV competition. Doing so allowed the team to determine the basic aspects of the AUV's hull, propulsion, sensor, and computer systems that would be critical to successful mission completion. The team concluded that the vehicle would meet the following restricting criteria and be capable of performing the following tasks:

- Fit in a box 72 inches long, 36 inches wide, 24 inches deep and weigh less than 100 kg.
- Autonomously submerge, depart from the starting point, and pass through a validation gate.
- Possess a control system capable of maintaining heading, speed and depth simultaneously.
- Detect and accurately locate an acoustic pinger operating at a frequency of 27 kHz.
- Visually detect a series of man made objects and determine the depth of their top surfaces.
- Visually recognize and read a pattern of bar codes printed atop the man made objects.

Mechanical Systems

Vehicle Configuration

The final configuration of the AUV builds on the robust configuration first employed by the Cornell AUV team two years ago, with watertight compartments attached to an external aluminum skeleton (Figure 1). In so doing, the vehicle is afforded incredible stability and modularity, with the ability to augment the sensor suite of the vehicle with minimum hassle. This year's AUV goes several steps further by increasing the environmental flexibility of the submarine and substantially reducing weight. The effect is to minimize complexity associated with operating the vehicle and increase the range of system capabilities.
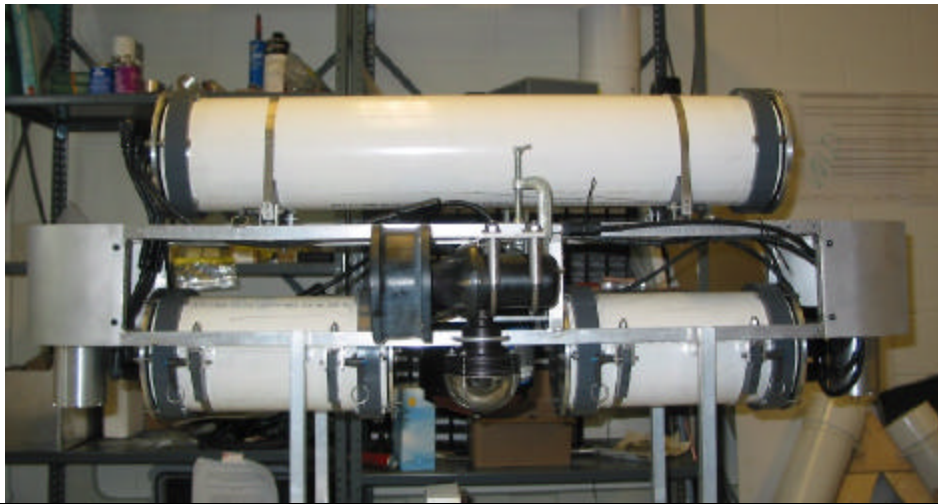

Fig. 1 Starboard Side View Showing 2002 Vehicle Configuration

Propulsion

A significant design challenge was presented by the competition's evolution to a deeper operating environment. Where teams in the past have not needed more than 18-20 feet of maximum depth capability, this year's competitors are required to operate up to 40 feet in depth to effectively encompass the entire competition arena within their vehicle's design operational range. Forty feet is substantially deeper than previous arenas, and hydrostatic pressures will exceed 2 atmospheres. Systems on the 2002 Cornell AUV were reevaluated and redesigned to be fully compatible with the deeper environment.

Primary areas of concern were the thruster motors which would propel the AUV. Thrusters of a type similar to those implemented in the past, such as trolling or bilge pump motors, are not designed for operation in water deeper than 5-10 feet. The manner in which a seal is formed around the output shafts of these motor types is incompatible with deep water operation, and would lead to flooding and eventual failure of the units. The solution for Cornell's AUV was to utilize two 6-inch diameter shrouded thruster motors from a HyBall ROV submersible, and to design and fabricate a second pair of 4-

inch diameter thruster units (Figure 2). All four thruster motors utilize rotating mechanical shaft seals around the output shafts and o-ring seals to maintain case integrity. The two HyBall thrusters have a geared output and function as the AUV's primary propulsion units for fore-aft and yaw control, while the direct-drive, custom-machined aluminum units serve as vertical thrusters for controlling the vehicle's depth. All four of the AUV's thrusters are rated in excess of 100 meters (~328 ft) operating depth, and operate on 12 volts DC.

Hull Modules

Fig. 2 Vertical Thruster Assembly

The submarine's three primary watertight compartments were also carefully designed to ensure that they would maintain seal integrity down to and in excess of 40 feet. The watertight compartments on this year's vehicle are constructed from 6-inch diameter schedule 40 PVC pipe, and sealed with custom machined aluminum end caps. Each end cap utilizes a molded urethane rubber bevel-type seal, which is kept in contact with the hull's edge via a PVC collar and retained with threaded hardware. The bevel-type seals are impervious to the vulnerabilities that can affect o-ring seals, such as scratched sealing surfaces or uneven compression. The nature of the end cap seals provides a very robust and reliable seal without the complexity of o-ring type seals that would be subject to a greater chance of failure given the high frequency of seal removal for servicing internal components.

Each of the three watertight hulls on the 2002 AUV houses a different set of components. The top electronics hull holds the submarine's CPU and associated power supplies, as well as any boards necessary for sensor signal conditioning and input to the CPU. Equipment in this hull is mounted to a lightweight internal frame, and all power and signals are routed to their external connectors via a blind-mating bank of socketed connectors at the end of the frame. Power is provided to the main hull in the form of 24 volts DC from a battery pack in the first of the two lower hulls. This hull, situated below the main hull and to the aft of the vehicle, contains two separate battery packs and the connecters necessary to route power to the main hull. Both battery packs comprise two 12V 5Ah sealed lead-acid gel-cells wired in series to provide two separate 24V 5Ah packs. One of these provides electricity to the vehicle's onboard electronics, while the other is an isolated, dedicated power supply for the DVL.

The final, and third, watertight hull is located forward of the DVL/computer battery hull, in front of the mounted DVL unit. This space serves as the motor power and control compartment for the AUV. In addition to two 12V 12Ah sealed lead-acid batteries wired in parallel to power the motors, this hull also contains all of the electronic speed controls that regulate the output of each thruster. The mini Serial Servo Communications device (SSC) used to set thruster speeds via an RS-232 serial port and

the Novak Super Rooster speed controls are linked to a power bus inside of the hull. This bus is switched by two 40A relays. When disconnected by an external kill switch, these relays render the vehicle completely safe and immobile. The motor-control hull is linked to the main hull via a single serial communication line. All three hulls are affixed to a central aluminum frame with stainless-steel locking pins, and can be quickly and easily removed for servicing or battery replacement.

External Wiring

A critical area of improvement for Cornell's 2002 AUV is the implementation of high quality external signal and power cabling, as well as robust through-hull routing via connectors and cables from Impulse Connectors. Rated for over 10,000 psi, a combination of cable and connector styles ensures compatibility with the deeper operating environment and full compatibility with corrosive salt-water or chlorinated environments. The cables were spliced using custom molded urethane rubber to encase joints and maintain cable integrity.

Power

A pair of Astrodyne DC/DC converters mounted inside the main hull provides power for the computer and sensor systems. One of the two converters provides a 5V at 12A to the Single Board Computer and logic sensor boards. The remaining converter distributes ± 12V to higher voltage devices and devices requiring a dual rail supply. These converters draw power from the battery pack providing a 24V DC source to the main hull.

Vehicle Dynamics and Control
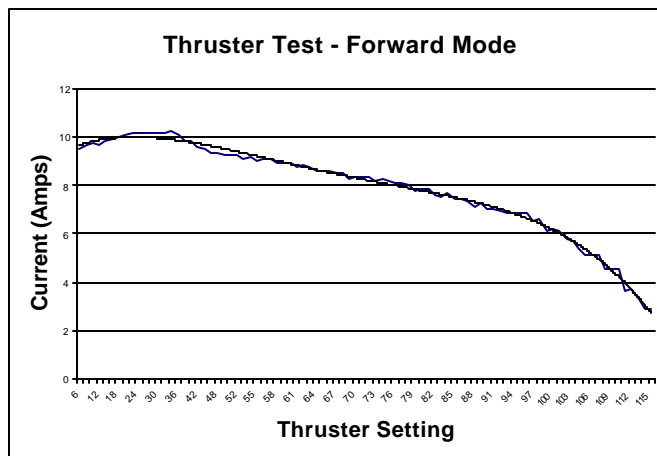
Fig. 3 Plot Showing Linear Thruster Response

A robust feedback control system maintains the depth, heading and velocity of the AUV during operation. A Proportional, Integral and Derivative (PID) controller maintains velocity and heading simultaneously, while a separate controller maintains desired vehicle depth. Heading and depth control are accomplished by a combination of proportional and PID control, depending on the magnitude of the error between desired and current heading values. The motor control settings, called τ, are digital signals that the motor controller converts to a current which in turn drives the thruster motors and propels the submarine. Prior to developing a control algorithm, we sought to understand the relationship between τ and current. The HyBall ROV motors and the 4-inch diameter thruster units were tested in a simulated environment to obtain curves of τ vs. Current.

Analysis of these plots revealed a range of τ values in which the thruster motors respond in linear fashion (Figure 3). Utilizing this linear regime simplified controller design and made obtaining system response curves a less-arduous process. The response curves resembled a second order, critically damped system. Controller coefficients were obtained via root-locus analysis of these linearized system response curves, and evaluated during in-water testing.

Sensor Systems

Hydrophones

The acoustic sensors consist of an array of four Digital Signal Acquisition (DSA) Modules. As depicted in Figure 4, each DSA consists of a hydrophone, an amplifier, an AD7664 analog to digital converter and a digital signal processor chip (DSP). The hydrophones are placed in a linear array along the AUV's external frame. Such a configuration allows each hydrophone in the array to sample spatially the acoustic wave front emanating from the pinger at different times. By calculating the difference in time at which each hydrophone detects a wave front and using triangulation one can determine a bearing to the acoustic pinger. To obtain the most accurate approximation of bearing one would maximize the spacing between the hydrophones. Consequentially, the time interval at which two or more hydrophones detect a wave front (i.e. path difference, Δ,) also increases.
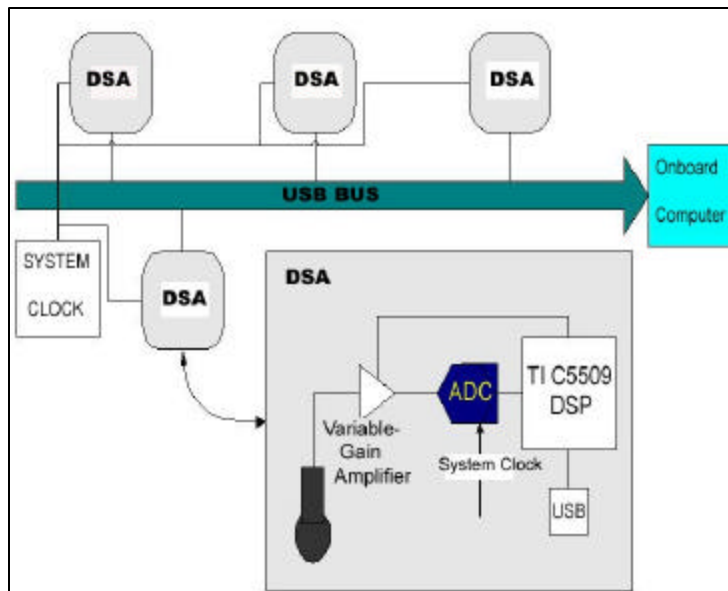
Fig. 3 Hydrophone DSA Configuration

Once the hydrophones detect a wave front from the pinger, the signal is amplified and then sent to the analog to digital converter. A digitalized signal is then sent to a digital signal processor (DSP). The job of the DSP is to process the signal with a Finite Impulse Response (FIR) filter. Each DSA is capable of acquiring filter coefficients from the on-board computer. After the signal is filtered, the DSP will evaluate a trigger condition. This will determine whether the signal is indeed from the pinger or if it is background noise. The DSP will consider the signal to be authentic and from the pinger if the signal's wave form is 10μs in duration. Following verification of a trigger, the DSP will store the signal in a buffer and send it to the on-board computer via a universal serial bus (USB). We opted for this method of communication because of the high 12

Mbits/sec throughput, the availability of DSP with an embedded USB device controller, and the robust error checking scheme employed by USB.

The on-board computer will process the acquired signal with a MUltiple Signal Classification (MUSIC) algorithm. MUSIC is a method of characterizing the range of the self-adjoined operator and separating the signal and noise subspaces[1]. By using linear algebra, one uses the signal input to generate a self-adjoined operator A and to also calculate the noise subspace P_{noise}. Since A is self-adjoined, we know that the noise subspace is orthogonal to the range. With this conclusion, a vector "f" (signal) is in the range of A if and only if the projection of it in the noise subspace is zero, which can be expressed as: $\dfrac{1}{P_{noise}f} = \infty$

Often used for determining the individual frequencies of multiple time-harmonic signals, MUSIC also contains an algorithm for applications in DOA (Direction of Arrival) determination, and it is this feature which is used to pinpoint a bearing to the acoustic source. Once the noise subspace is calculated, the MUSIC spectrum is calculated as

$$S(\boldsymbol{q}) = \left[\frac{L}{UVV*U*} \right] \text{ where } U = \begin{bmatrix} 1 \\ e^\wedge i\boldsymbol{p}\sin(\boldsymbol{q}) \\ ... \\ e^\wedge(L-1)i\boldsymbol{p}\sin(\boldsymbol{q}) \end{bmatrix} \text{ and } V = \begin{bmatrix} E_{N+1},...,E_L \end{bmatrix}$$

L = number of antennas (hydrophones)
N = number of uncorrelated sources

RDI Workhorse Navigator DVL

The Workhorse Navigator DVL provides precision velocity and altitude information required by the AUV's control systems. The DVL is also responsible for supplying position feedback and a profile of the floor terrain to the on-board computer's navigational system. The DVL acquires its information about the outside world through four acoustic transducers mounted on its lower face. These operate at a frequency of 1200 kHz and utilize Doppler shift and signal return times to determine velocity and altitude information, respectively.

Mounting, Powering and Connecting the DVL

The DVL is mounted on the AUV's centerline, with the bottom of the transducer head slightly above the bottom of the lower hulls. This configuration protects the instrument in case of an accidental contact with the bottom. Its mounting ring is electrically and mechanically isolated from the AUV's frame via rubber standoffs.

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[1] Schmidt, Ralph O. "Multiple Emitter Location and Signal Parameter Estimation", *IEEE Transactions on Antennas and Propagation Vol AP-34, No.3 March 1986*

The DVL operates from a 24V DC supply. The vehicle's onboard 120 watt DVL battery pack allows for several hours of continuous operation before the batteries need to be refreshed. Communication with the AUV's onboard computer is accomplished by using a standard RS232 serial link. Configuration commands are programmed into the DVL prior to the start of a given mission, stored into non-volatile memory, and retrieved immediately prior to DVL activation.

DVL Applications

The DVL's capabilities allow it to provide input to a wide range of AUV subsystems. One of its duties is the provision of velocity and heading information to the vehicle's motor control software. Accurate, three-dimensional velocity data will afford an unprecedented level of control and elegance to the 2002 AUV's movements. Depth control is another area where the DVL shines. The DVL's ability to report altitude information accurate to the centimeter allows the AUV to hold a constant altitude over the bottom and follow bottom terrain with ease. The DVL's ability to precisely track its course through the water lends a deduced-reckoning capability to the AUV that will greatly simplify navigational efforts and considerably aid in the location and identification of the target objects. With the aid of the DVL, the AUV can be programmed to follow a given path, diverging from and returning to that path as necessary.

Target location and identification is aided by the AUV's ability to individually monitor each of the DVL's four transducer beams. Since the pulses from each transducer strike the bottom in different locations relative to the AUV, a sudden jump in the height reported by one transducer indicates the possible presence of a target beneath that transducer's beam. Additionally, the transducers' four independent altitude measurements allow an altitude gradient to be measured and oriented in space. If the AUV is in the bowl at the center of TRANSDEC, altitude gradient information will be compared against the AUV's current depth and heading. Since every location within the bowl has a unique depth and direction for its gradient, the AUV's position within the bowl can be determined.

Pressure Sensor

To accurately determine its vertical location with respect to both the surface and the bottom of the arena, the AUV is equipped with a Measurement Specialties Incorporated MSP-600 analog pressure transducer which is interfaced to the computer via a custom designed signal processing card. The pressure transducer measures between 0 and 50 psi absolute pressure, and reports a differential voltage between 0.5V and 4.5V DC. This voltage is amplified and converted to a digital signal before being conditioned and transmitted over an RS-232 serial interface to the CPU, where it is continuously translated into a depth indication and logged in the vehicle's shared memory structure.

Vision System

The AUV's vision system consists of an onboard camera, a frame grabber, and vision processing software. The purpose of the vision system is to correctly scan and read a barcode situated atop the man made objects. Commands from the artificial intelligence (AI) instruct the frame grabber to record images from the camera when the presence of a target box is detected. The vision software is then used to decrypt the barcode in the frame. First, the image is converted into a Boolean matrix. The true points in the matrix resemble where the barcode is oriented. Next, the vision software rotates the entire matrix, via linear algebra techniques, so that the barcode is correctly aligned for the parsing process. The parser then takes a single row from the matrix and searches it for the numerical value encoded in the barcode. Comparing the widths of the bars against each other to determine which bars are binary "ones" and which are "zeros" accomplishes this task. The resulting binary number can be easily converted to decimal and reported to the shared memory process.

Computer & Software Interfacing

The 2002 vehicle's software interfacing consists of the path planning or artificial intelligence (AI), motor controls, and data acquisition. The data acquisition interfaces with the different onboard sensors, including the DVL and depth sensor, and gathers real time data. The artificial intelligence acts on the data and dictates desired actions, which are executed by the motor controls.

The most important operation performed by the AUV's computer is gathering data from the sensors. Data from the DVL and depth sensor are obtained several times a second via the data acquisition software. The data is uploaded to shared-memory where other processes and programs have access to it. Because the data acquisition software is running as a separate process, other functions can be carried out as data is continuously updated to the shared memory.

At the heart of the submarine's computational functionality is the system's artificial intelligence (AI). Decisions are made by the AI, which has constant access to the shared memory where real time data is stored. Because of C++'s support for object oriented programming, it was the obvious choice to compose the artificial intelligence portion of the software. All commands to the submarine are carried out through an object oriented class called "AUV". When several commands are put together to perform a portion of the mission, the commands are grouped into a custom made structure called a procedure. There are a handful of procedures that are used to complete the mission. These include, "initialize," "go through gate," "go to pinger box," "search for inner cluster," "search for outer cluster," "return to dock," and "shutdown." Other procedures that are used for testing and configuring the AUV were "calibrate motors," and "driver." The procedures are put in a queue in the beginning of the program and executed sequentially. When a procedure is executed, it is forked as a separate process. As a process is running, the high level AI software checks for errors. If an error is discovered

all running procedures are aborted and the AUV returns to the surface. This design was chosen because of its modularity. If a part of a system needed to be modified, it could be replaced without making major changes to the rest of the infrastructure. For instance, if a portion of the mission needs to be done in a different order or taken out entirely, switching the order of the procedures in the queue would be sufficient. Commands to the vehicle's systems through the AUV class can be easily modified without having to change any commands in a procedure.

Much like the data accusation, the motor control system runs as a separate process in the background. Using information from the data accusation and requests by the artificial intelligence system, the motor controls system operates the thruster motors. The requests from the AI are made when one of the functions from the AUV class are called. This informs the motor controls that a new setting is desired. Through serial port connections, thrust settings are delivered from the motor control software to the Electronic Speed Controls powering each of the four thrusters.
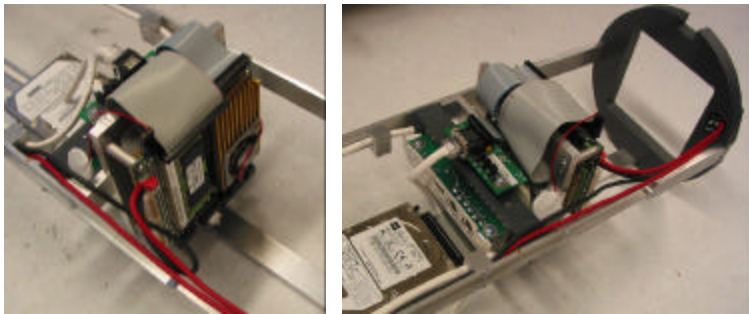

Fig. 5 CPU Installation

Conclusion

Cornell University's 2002 AUV has been designed from the ground up to succeed in the face of complex challenges presented by the 5th IAUV competition's rules and location. The combined efforts of the team's 17 members and faculty advisors will ensure a robust and reliable performance in San Diego. Incorporating 2 previous years of successful design experience in addition to multiple innovative improvements, CUAUV is in a position to accurately and efficiently survey the TRANSDEC pond during the 2002 competition.

Acknowledgments