

Cornell AUVSI Competition Entry 2005

Cornell University Autonomous Underwater Vehicle Team (CUAUV)

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ABSTRACT

This paper presents the 2005 Autonomous Underwater Vehicle (AUV) designed by the Cornell University AUV Team. This year's vehicle builds on the team's previous iterations and maintains the aspects that have proven to be successful in the past, including a dual hull structure, brushless motors, explicit separation of hardware by functionality, and flexible software. Significant improvements made this year include a modular sensor infrastructure, signal and power backplanes, enhanced power management, and improved vehicle control.

1. INTRODUCTION

CUAUV has competed in the AUVSI underwater competition for the past 6 years. Each year we have made significant improvements to the vehicle's design and functionality, and this year has been no different. We built on last year's experiments with modularity to produce a vehicle designed from the bottom up with sensor and signal modularity in mind. Combined with existing support for software modularity, the 2005 vehicle is poised to be a versatile platform that can not only succeed in the AUVSI competition but that also offers opportunities for research and applied field work. This paper describes each area of the CUAUV 2005 vehicle in detail. Section 3 begins with an explanation of the vehicle's overall structure. Sections 4 and 5 describe the various hardware and their functionality as broken down by physical internal location. Section 6 lists existing sensors and details improvements made this year. Section 7 describes the software architecture and functionality, and Section 8 concludes the paper.

2. THE MISSION

The 2005 competition will again be held at the Transdec facility at SPAWAR in San Diego, CA. This year's mission is similar to previous missions, challenging the vehicle's ability to perform vision processing, acoustic sensing, independent control, and decision making. An added challenge this year is the requirement that the vehicle determine the frequency and color of a flashing light, in order to decide the order of task completion.

The three tasks for this year's mission are docking, pipeline surveying, and acoustic beacon location.

- The docking station is a submerged, vertical, transparent PVC pipe enclosing a light. Successful docking occurs when the pipe is tipped by the vehicle.

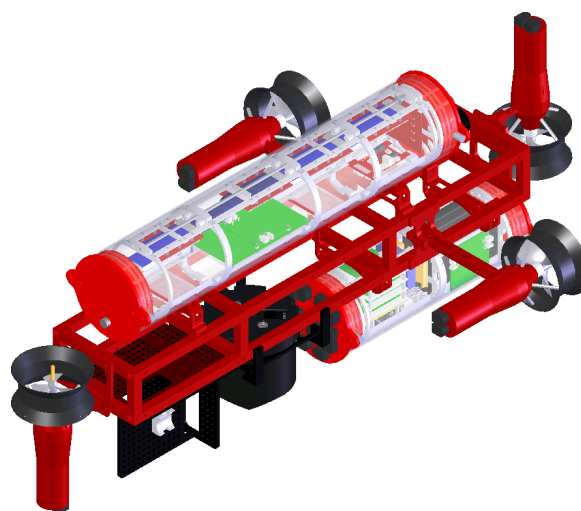


Figure 1: CAD Model of the 2005 CUAUV Vehicle

- The pipeline is a series of colored PCV pipes with a break in the middle. A colored bin is located inside the break. Successfully identifying the break involves dropping two markers directly into the bin.
- The recovery zone is a small hexagonal area around an acoustic pinger. Successful recovery occurs when the vehicle breaches the water's surface within a set distance of the pinger.

The vehicle begins the a mission run by submerging. It then navigates under a submerged gate, and proceeds to complete the three stations in the order designated by the color and frequency of the flashing light.

3. OVERALL DESIGN

A dual-hull design was selected for CUAUV's 2005 vehicle; this configuration has been successfully implemented by CUAUV in the past. The hulls are filament wound carbon-fiber tubes with a redundant o-ring sealed endcap at each end. Endcaps can be easily removed with 2 quick-release pins. Vacuum ports on either tube allow a vacuum to be pulled inside the vehicle, which can be used to ensure seal integrity through the mission. The two hulls, four thrusters, and all external sensors are attached to an aluminum frame.

The combination of a large and light upper hull with a small and heavy lower hull keep the center of buoyancy high and the center of mass low. This geometry avoids the need for roll thrusters because of its passive roll stability. The upper hull houses computers, microcontrollers, and other mission relevant hardware, while the lower hull houses the batteries, power, and thruster drive equipment. This explicit separation of hardware by functionality decreases interdependence; equipment in one hull can be replaced without modification to the other hull. [2]

3.1 Thrusters

The propulsion system was designed to be efficiently hover-capable with precise control while using low power. To provide forward and backward propulsion, as well as yaw control, a pair of thrusters are mounted parallel to the hulls. Another pair of thrusters are mounted vertically at the ends of the frame to provide depth and pitch control. Each thruster is custom designed around a 70W Maxon brushless motor, geared down 4.3:1 to yield an approximately 1500 RPM operating speed. (See Figure 2) A magnetic digital position encoder allows us to control the drive shaft to within 1/500th of a turn. Custom propellers were designed and manufactured using armored stereo lithography. Thruster housings can be oil-filled to allow operation at full ocean depths.

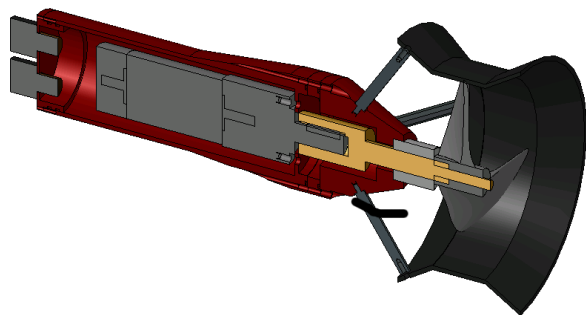


Figure 2: Integrated Thruster

3.2 Sensor Mounting

Sensors are mounted to an area on the front underside of the frame. A “T” shaped delrin piece is attached to the frame such that the “T” points forward. Each sensor is first attached to a mounting bracket, and then mounted to the “T” using a standard hole pattern. This design allows us to mount a sensor pointing in nearly any direction- downwards, forwards and sideways.

4. UPPER HULL

4.1 Endcap

The upper hull endcap has two Seacon “pie” connectors, which wedge shaped connectors plug into. Each sensor’s cabling terminates into one of these wedges and can plug into any slot on the pie connectors. CUAUV has defined a specific purpose for each of the pins on the wedge connector. The uniform connector and signal specifications allow sensors to be easily mounted and connected to the vehicle without compatibility concerns.

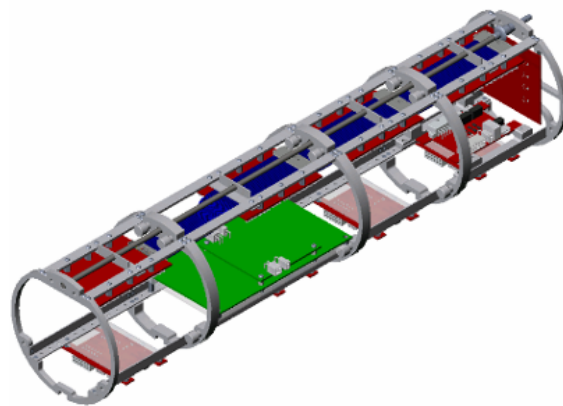


Figure 3: Upper Hull Rack

4.2 Mechanical

The upper hull rack uses a modular mechanical approach consisting of removable rack segments. (See Figure 3) The segments can be added or removed without tools, enabling rapid reconfiguration and maintenance. CUAUV’s vehicle currently uses six and nine inch rack segments, though segments of any length could be integrated in the future. Any number of segments can be added in any configuration so long as they fit within the hull. In order to support the different spacing from the front endcap, CUAUV has implemented a mechanical latching system that latches regardless of the number or configuration of modules in the upper hull.

4.3 Signal Board

One of the biggest issues in reconfiguring and upgrading AUVs is routing the necessary wiring to new devices. CUAUV uses a series of signal backplane boards to maintain signal integrity throughout the vehicle. The signal boards are connected using 80-pin, impedance matched Samtec cables. On each board, the signals are broken out onto Molex connectors. Because corresponding Molex breakout connectors are electrically connected through the Samtec cable, establishing device connectivity is greatly simplified. Any two devices can be connected together merely by connecting them to corresponding signal board connectors.

4.4 Power Board

Each segment in the upper hull also has its own power routing board. Structured similarly to the signal backplane boards, each power backplane board accepts a main power cable coming in on one side and going out on the other. The power backplane carries +5V, battery voltage, and ground. Each board then provides board to electronics in its segment by tapping the main power lines.

A PIC microcontroller on each power backplane board is capable of monitoring individual devices’ current draw as well as controlling a relay that can turn power on and off. The microcontroller reacts to commands over a built-in I²C bus. The master devices on the bus (usually a NetBurner) can therefore issue commands to control power to any device in the hull or request power draw information about any device.

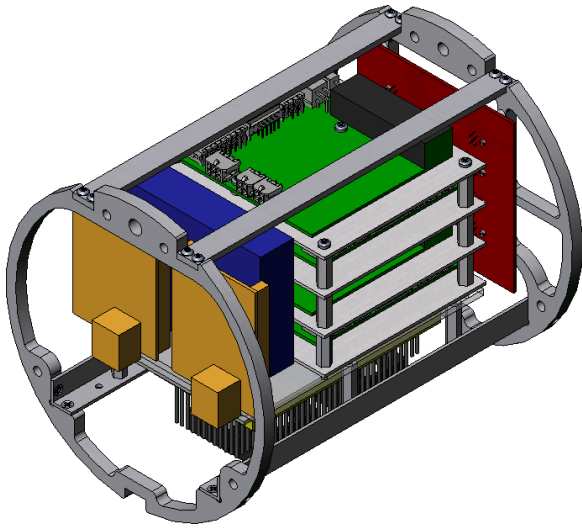


Figure 4: Power Management and Controllers

4.5 Computing Hardware

The majority of onboard processing is run on a VersaLogic 1.6GHz Pentium-M single board computer located in an upper hull rack section (Figure 3). The functionality provided by this upgrade is substantial: we are able to handle both vision processing and mission execution on the same platform without degradation in scheduling latency.

5. LOWER HULL

5.1 Mechanical

The lower hull is mechanically divided into two sections. One section specifically houses batteries. The other section contains the power management and motor controller hardware. This division allows for upgrades or modification to one aspect of the system without affecting others.

5.2 Motor and Controllers

Four Maxon EPOS 24/5 motor controllers are connected over a CAN bus, with the head controller connected over RS-232 to a NetBurner microcontroller unit. The NetBurner reads control desires from the onboard computer and appropriately controls the various thrusters. Basic safety and regulatory measures are in place on the NetBurner to prevent catastrophic mechanical behavior. (See Figure 4)

5.3 Power System

CUAUV's 2005 power system was designed to provide flexible power options and easy monitoring, while remaining streamlined. Several other features were required, such as the ability to supply power over the tether. Batteries and power management boards are located in the lower hull due to weight concerns. A power source switching module is located in the upper hull. Plugging the tether into the lower hull enables the AUV to seamlessly charge batteries while running. Similarly, plugging the tether into the upper hull enables the AUV to keep electronics powered while swapping batteries. The ability to charge over tether will be particularly useful when the team's docking solution is fully developed. The lower hull battery management hardware is



Figure 6: Custom Camera Housing

based on a system built by Ocean Server. It includes functionality for battery status management, switching between power sources, and battery charging. (See Figure 5)

A battery pack from Inspired Energy was selected. The twelve-cell pack (four in series, three in parallel) provides 95Wh of energy. The batteries are compliant with the Smart Battery specification. They are therefore able to monitor their own health and report to the Ocean Server via SMBus (a derivative of I²C bus). The combination of the Ocean Server and Smart Battery technologies allowed us to design a modular battery system. Our normal module will consist of four battery packs, providing about 400Wh of energy to the sub. However, we are also able to develop larger modules in the future that could contain up to eight battery packs. Each battery module is an individual entity, separate from other electronics. We are therefore able to build several identical modules that can be quickly and easily swapped out of the AUV.

6. SENSORS

6.1 NetBurner

As in our 2004 vehicle, NetBurner Mod5282 microcontroller units are used as intermediaries between sensors and other processors. Signals from sensors are received by the NetBurner devices, processed, and retransmitted over the vehicle's Ethernet network in the form of a UPD multicast packet. This added interface layer allows higher level functions to be isolated from the specifics of how each sensor operates. The afforded sensor modularity contributes to overall vehicle modularity.

6.2 Camera

Machine vision data is captured through two firewire cameras in custom enclosures. We read in full 1.3 megapixel frames from each Pixelink PL-A742 camera. The cameras are equipped with 8mm C-mount lenses and interface to the vehicle over custom underwater cabling that contains two power conductors and 3 twisted pairs (also used on the vehicle for power, Ethernet, tether and thruster cables). The cameras have a sapphire viewport, which is scratch-resistant, yields high depth ratings at a small thickness, and minimizes optical distortion. (See Figure 6)

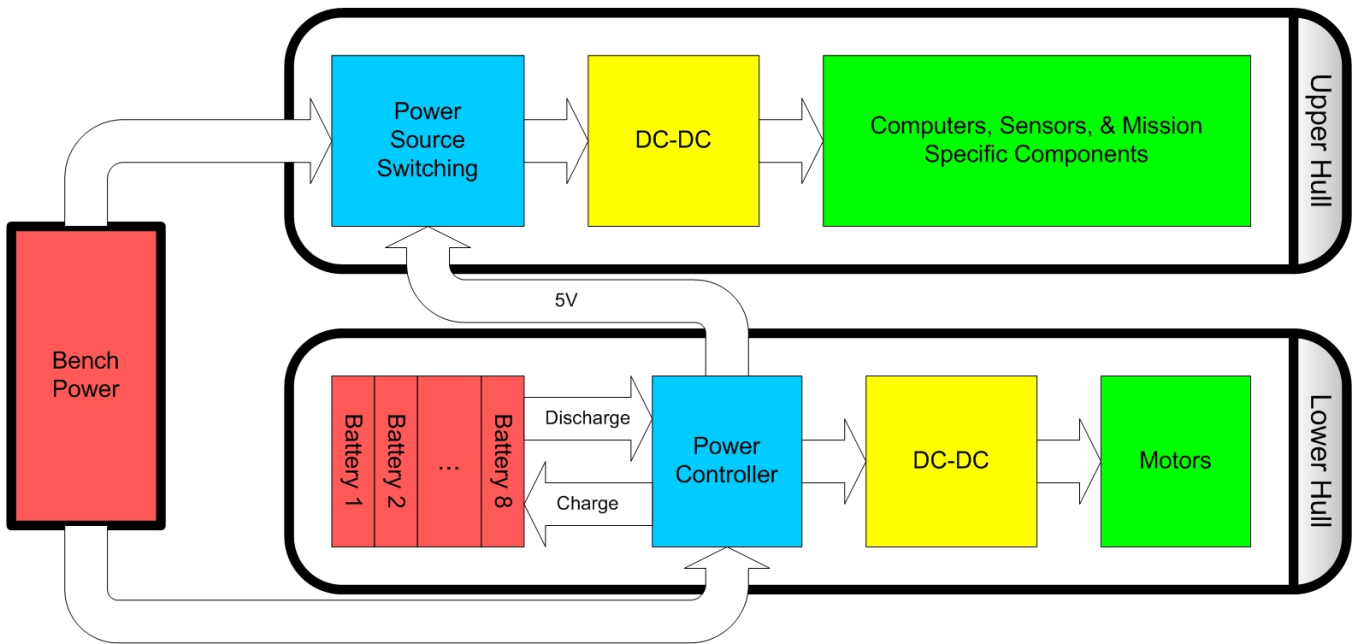


Figure 5: Overall Power Structure

6.3 Hydrophones

In order to obtain absolute navigational information, a method is necessary for determining the location of the AUV relative to some object of known location. Two popular methods for acquiring this information are Long Base-Line (LBL) and Ultra-Short Baseline (USBL) sonar systems. Our vehicle uses a USBL navigation system to determine positional information relative to an acoustic transponder (pinger). Our USBL system transmits an estimated bearing to each ping it receives, along with the calculated pinger frequency, and the estimated signal power which can be used to determine the approximate distance to the pinger.

The lack of reliable range information in the passive SONAR problem (in lieu of computationally intensive, and finicky matched-field algorithms) has motivated a further development. USBL systems need to have closely-spaced sensors in order to obtain unambiguous DOA estimates. Unfortunately, this requirement means that near-field beamforming, which can produce range information, can only be performed at extremely short distances: for example, at 30KHz, the near field extends approximately 10cm from the array. We have devised a solution to widen the baseline and achieve range information on the somewhat larger scale of up to 10 meters. We use a pair of USBL units with a known geometry. range information can be obtained with very low variance in the near field via the differences in DOA reported by the two sensors and the displacement vector between them. This Short/Ultra-Short Baseline (SUSUBL) system has yet to be verified, but we hope to use it to good effect for close-range acoustic navigation.

Our USBL system is entirely custom-developed. It is small and lightweight, housed in a 4.5" long, 2.5" outer diameter acrylic tube. Power, and RS-232 serial communication is provided by a single 10-pin underwater connector. The

system draws 340 milliamps, and requires only a single 5-10 volt DC power supply to operate. The enclosing tube has o-ring sealed end-caps at each end; one cap houses the interface connector, and the other has the 8 transducers molded directly into it, achieving a low-cost integrated array mounting solution.¹ The array elements are rectangularly spaced, 4 horizontal by 2 vertical. This configuration provides high-resolution azimuthal direction estimates and the ability to discriminate in elevation.

Internally, the system is based around a single MOD5282 module by NetBurner. The main advantages of using an off-the-shelf computing platform are numerous, including far lower cost² and minimal development time.

We developed a custom PCB that plugs directly into the NetBurner module, and shares its tiny 2" x 2.6" footprint. This PCB holds the power distribution circuits for the NetBurner, power conditioning circuits for the sensitive amplifiers, an 8-channel analog front end with software-controllable gain, and two 4-channel simultaneous-sampling A/D converters, along with an RS-232 transceiver. The converters are mapped directly into the MCF5282's memory space for high-speed parallel reading, and the gain control resistive D/A converters are connected to a single synchronous serial port for simple one-command settings.

The PCB uses 4 layers, with one layer including a split ground plane to provide separate ground return paths for the analog and digital circuitry, and provide some noise im-

¹The cost of the entire array is about \$200.00, which is very low compared to the cost of even a single commercially packaged transducer

²A 4-layer PCB would cost around \$200.00 to manufacture, not to mention the cost of the IC's themselves, a NetBurner module costs \$100.00

munity. The 4-layer architecture permits the compact form factor, and provides protection of the sensitive analog signals.

A single channel of the analog front end structure is comprised of two gain stages and a buffer stage; the stages are AC coupled to provide zero DC offset at the converter inputs. The first stage is a low-noise monolithic instrumentation amplifier, providing 40dB of clean front-end gain,³ while subsequent stages use low-cost, low-power op-amps. Variable gain is achieved by varying the input resistance to the second stage using a digital potentiometer (RDAC). This design allows a wide gain range, and permits this stage to also contain a 1-pole low-pass filter to attenuate out-of-band noise and RF interference. There is no anti-aliasing filter in the analog signal chain, and this choice is deliberate: it allows us to demodulate narrow-band ping signals to a lower frequency where phase differences can be more precisely measured. The final stage is a unity-gain buffer to drive the low-impedance ADC input.

The ADC interfaces with the MCF5282's built-in asynchronous memory port, so that the sample read can be performed by a single `LOAD` instruction for minimal processor overhead. The ADC sample rate is software selectable: the sample clock is one of the MCF5282 PWM outputs.

In software, samples are matched filtered to maximize SNR, and a power threshold detector isolates acoustic events of interest. When an event is detected, it is Fourier transformed, and the covariance matrix is calculated at the frequency of maximum energy. The direction of arrival of the ping signal is determined in both the azimuth and elevation axes using the MUSIC algorithm, [1] along with a frequency-dependent array steering vector estimator.

An extremely simple gain control algorithm maintains sampled pings at close to full-scale at the ADC input. If full-scale samples are detected, the gain is decreased by 1dB, otherwise, gain is increased unless the event contains samples which are within close tolerance of full scale.

7. SOFTWARE

7.1 Architecture and Organization

The CUAUV software architecture is designed around a specific set of concrete goals:

- Division of responsibility across processes.
- Division of computation across hosts.
- Ease of dockside control and debugging.
- Ease of software development.

The focus of the CUAUV software infrastructure is therefore on techniques that allow this separation of control, organized around two methods for communicating between processes and across hosts (IPC). The first of these methods is a performant shared variable scheme for periodically-updated state values, including sensor readings and desired thruster

³The AD623 from Analog Devices

settings. The second is a network-transparent remote procedure call (RPC) scheme for command-style operations. A particular process on a particular host interacts with other processes through the set of shared variables with which it interfaces, and through the RPC services that it calls or exports.

The RPC implementation is directly network-transparent: on initiation, an RPC connection negotiates the most efficient transport, either TCP or a local domain socket, between the two hosts. An efficient custom UDP multicast protocol synchronizes copies of specific shared variables across multiple hosts and the real-time microcontroller layer (discussed in Section 6.1).

Software component development is simplified by providing support in the core libraries for a variety of process implementation languages, including C++, pure C, C#, and the Ruby scripting language. Processes written in any one of these languages are able to communicate with other processes written in all of them; values are marshaled to a common, endian-safe intermediate format and unmarshaled to native language types.

7.2 Suite Functionality

The software infrastructure described in Section 7.1 is intended to support a substantial suite of components, each implementing a particular piece of AUV functionality. These components include:

- Feedback control loop.
- Comprehensive logging daemon.
- Simulation environment.
- Mission execution engine.
- Vision capture and processing framework.
- Probabilistic state estimation engine.
- Graphical interfaces to the functionality above.

The more significant of these components will be described in detail below.

7.3 Simulation

The vehicle and environment simulator is an extremely important piece of the CUAUV software suite. It allows us to test component integration, mission design strategies, and even vision processing concepts, in the absence of pool time and in an automated fashion.

Our simulation environment is separated into two components: a simulation daemon, which mimics vehicle response, models sensor behavior, and handles environment interaction; and a visualization interface, implemented on top of an OpenGL visualization library, which allows the user to visually interpret simulator output.

7.4 Mission Design and Execution

Central to our AUVSI competition entry is a set of tools for the design and execution of custom mission plans, built as a domain-specific visual language. Two components are central to this effort: a mission execution engine, which autonomously executes saved missions, and a mission design interface, which allows any user to visually design, manipulate, and test potential missions.

The visual language at the heart of this architecture divides mission designs into three features: tasks, which implement a particular domain-specific action; variables, which communicate information between tasks; and triggers, which synchronize threads of task execution. A mission contains an arbitrary number of threads, each of which contains a set of synchronously-executed tasks. On completion of its action, a task transfers control to the task connected by one of a set of branches specific to the task type.

Missions designed in this architecture can be built by reusing well-tested tasks in a way that accomplishes a mission-specific goal. This toolset allows missions to be easily designed, tuned, tested, and run.

7.5 Vision Processing

Another component particularly critical to the AUVSI competition is the vision capture and processing daemon, responsible for communicating with the vision sensor suite (Section 6.2), logging captured video, and processing frames when they are requested by the mission engine. Such requests are made through calls over the RPC layer to the service exported by the vision daemon.

A variety of vision processing schemes are used to handle each of the numerous competition tasks requiring machine vision: gate transit, the order selection light box, the docking station, pipeline following, and marker placement. The long, rectangular objects present in both gate transit and pipeline following are identified by locating the most likely object positions in each row, then fitting a linear model to those points. The marker placement area is determined by locating both the high-contrast area around the box and the specific box geometry. Finally, the light box positions and light frequencies are determined by processing a straightforward color-thresholding detection algorithm at a reasonable sampling rate.

8. CONCLUSION

CUAUV's 2005 entry is a substantial improvement over previous Cornell entries in nearly every respect: a dramatic increase in onboard computational resources, much more effective vehicle control, better internal and external component modularity, and significant improvements to software suite functionality. We are confident of the capability of our entry, and look forward to testing its performance in the 2005 AUVSI underwater competition.

9. TEAM MEMBERS

The 2005 CUAUV team is comprised of Kyle Archie, Eli Brown, Wei Min Chan, Shawn Chen, Ben Evans, Brad Factor, Sam Fladung, Caspar Floryan, Bassem Ghali, Tingwei Huang, Siddharth Inamdar, Shashi Jain, Morgan Jones,

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11. REFERENCES

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