Design Specifications of the Big Red Artifical Intelligence Navigator

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Abstract

The design of Autonomous Underwater Vehicles (AUVs) is a unique area of engineering development that has exciting potential for a variety of tasks. The Cornell University AUV team has accepted the challenge of developing AUVs by entering the 2000 International Autonomous Underwater Vehicle Competition. This competition entails the design and construction of an AUV capable of locating and retrieving a marker based on audio and visual signals. The vehicle must be completely self-contained and cannot make use of outside sources of information, such as a cable tether, wireless connection, or GPS signals. Our answer to this challenge is a fast, maneuverable, intelligent vehicle that can perform all of these tasks while complying with competition specifications regarding its maximum weight, power, and level of safety. Our AUV is capable of speeds up to 2 mph. It is able to detect both audio and visual stimuli and uses this information to locate an object. It can also pick up, secure and verify possession of the ring used in the competition. These capabilities allow our vehicle to successfully complete the mission requirements put forth by the AUVSI.

Introduction

Autonomous Underwater Vehicles (AUVs) allow their users to perform previously impossible tasks. By separating the operator from the chain of control autonomous vehicles can be deployed to perform completely unattended tasks. This allows many vehicles to operate simultaneously without human supervision, making these vehicles ideal for search and retrieval operations. This capability could dramatically decrease the time taken to recover objects – such as parts of downed airplanes – from the bottom of the ocean. The autonomy of these vehicles also makes them well suited for dangerous missions, where sending human operators is not feasible. By entering into this year's AUV competition, the Cornell University AUV team has assembled a device with potential applications in many of these areas.

Mission Strategy

This year's competition calls for the design and construction of an autonomous underwater vehicle capable of a number of different tasks. First, the AUV must submerge under its own power and locate a beacon that emits both an audio ping and a light flash. The AUV must then retrieve a ring attached to the beacon and bring it to the surface. The AUV must accomplish these tasks within thirty minutes and must comply with the imposed weight and safety requirements.

We have developed a simple but effective strategy to successfully complete the mission:

1. Initialize: The AUV has not detected any signal from the target. It moves towards the center of the arena to get into audio range
2. Approach: The AUV detects a ping from the source. It recomputes its path to move towards the beacon.
3. Scan: The AUV is now near the source of the ping and begins a visual search of the area for a ring or flash.
4. Commit: The position of the ring is confirmed within satisfactory error bounds, and the AUV performs its final approach to retrieve the ring.
5. Surface: Once the ring is retrieved securely, the AUV surfaces to end the mission.

Mechanical Systems Overview

Hull and Propulsion

The mission for this year's competition required the construction of an AUV capable of submerging and surfacing, housing sensitive computer equipment, locating and retrieving a beacon in a lake, and maneuvering under its own power for up to one half hour. Therefore, our team's goal was to build a reliable, robust vehicle with sufficient dry housing space, which could maneuver with maximum speed and efficiency while complying with competition-specified power and weight constraints. The AUV we have developed is capable of speeds up to 2mph while fully submerged, and can run for more than two hours on a single battery charge. Its modular design allows us to rearrange and service components inside the pressure hulls and quickly disassemble the entire vehicle for ease of maintenance and transport.

The most obvious feature of our design is the use of two pressure hulls located in the same vertical plane. This design arose from the desire to ensure the static stability of the AUV. By placing all of the batteries (the heaviest components of the AUV) in the smaller bottom hull and housing the electronics in the larger upper hull, we developed a vehicle with its center of gravity well below its center of buoyancy, resulting in outstanding static pitch and roll stability.

We considered several materials, such as standard PVC, aluminum, and Lexan to construct the pressure hulls; and eventually decided on ducting PVC due to its low cost, availability, light weight, and strength. The end caps for these pressure hulls were constructed from PVC sheets. These caps provide a fillet-type silicon seal when tightened down using the threaded rods installed for that purpose. The hulls are secured to a central aluminum frame using nylon strapping that enables us to quickly disassemble the entire vehicle. The top hull contains a removable internal frame that enables easy access to all of the AUV's electronics.

The Hull of the AUV

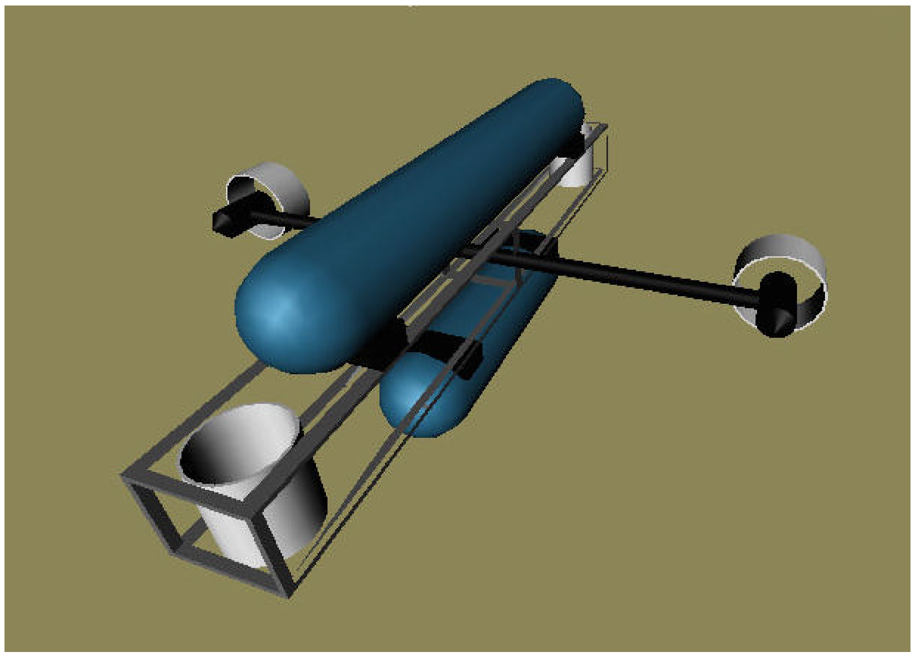

Figure 1: The double hull design of the Cornell AUV

The internal frame is an aluminum and PVC construct that fills the upper hull of our vehicle. The rack has two levels, the upper at the midpoint of the hull and the lower three inches below it. By placing the upper rack in the center of the hull we have achieved a maximum allowable component size. Large components can be placed on the upper level while smaller components and boards can be stored below. A notch and key mechanism ensures that the frame will always maintain its radial orientation within the hull.

The vehicle's main propulsion system consists of two side-mounted Minn Kota trolling motors. These motors were selected due to their efficiency and thrust (30 lbf each). They are also pre-sealed, removing many of the complications associated with ensuring correct underwater operation. The wide, side-mounted configuration enables high-speed forward and backward operation and yields a high turning rate. All the vehicle's motors are controlled via speed controllers designed for use with radio controlled vehicles.

Depth control is achieved by with two vertically-mounted thrusters fashioned from bilge pump motors. This depth control system was chosen over variable ballast approaches and other thruster configurations due to its simplicity and efficiency. We designed the vehicle to be approximately neutrally buoyant, allowing us to use smaller thrusters, and therefore less power, to maintain or alter the AUV's depth. Fine tuning of the overall vehicle mass and trim is accomplished using our ballast system, which allows us to adjust the weight as well as to distribute it along the roll axis of the vehicle.

Retrieval Device

One of the goals of the competition is to retrieve, secure, and surface with a ring. We settled on a hook array in order to accomplish this task. The apparatus consists of several hook mechanisms, each of which can independently secure the ring. Each mechanism can also alert the Artificial Intelligence module that the ring has been secured.

The passive sensor device is the simplest of four different designs which we have considered. As the loop moves towards the back of the mechanism it trips a lever (the long, red arm in the diagram) connected to a microswitch. Once the ring is at the back of the mechanism, it is trapped by the lever and blocks two infrared emitters which then confirms the ring's presence.

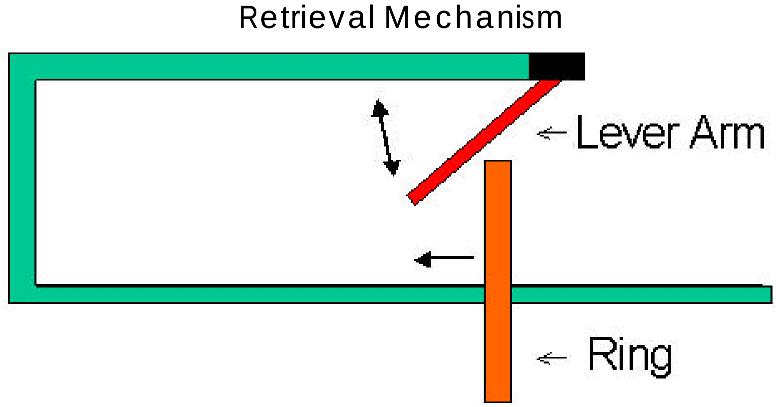

Figure 2: Retrieval Device Mechanism

Power Distribution

The vehicle is powered by a set of six 12 amp-hour motorcycle batteries and one smaller 5 amp-hour battery. All batteries are gell-cell, lead acid type, as the competition-specified. The six larger batteries are housed in the bottom hull, and power the AUV's Inertial Navigation System, vision system, thrusters, and other electronics. Four of the batteries are dedicated to the thrusters, and are isolated from the rest of the power grid to reduce noise. The other two large batteries are wired to a power supply which regulates the voltage and distributes it to the more sensitive electronics aboard the vehicle. The small battery in conjunction with the power supply provides the hydrophone array with its own the necessary voltage levels.

Sensor Systems Overview

Camera System

We decided to use the STH-V2 Integrated Stereo Head by Videre Design, which consists of an IC motherboard with mounts for two daughter board camera modules. Each camera module contains a complete CMOS camera with an image size of 320 x 240 pixels. The cameras are driven from a common clock so that their outputs are fully synchronized. A particularly attractive attribute of this camera system is its line interlace mode. In this mode, alternating scan lines from the camera output are interlaced making a single image, so that a single frame grabber is suitable for use with both cameras.

Hydrophone System

The sonar system employs four hydrophones in a tetrahedral array. By determining the time differences as the pings hit each hydrophone, the location of the target can be determined. The system first filters the signal with a high order, high Q filter to eliminate noise at all frequencies but the desired 27.5KHz. Then it adds gain on the order of x1000 until the noise level is approximately a half Volt. This is accomplished through an automatic real time gain system controlled with an Atmel 8515 micro-controller. The signal is then rectified, enveloped, and compared with a threshold level to determine when a ping has hit. The micro-controller takes the output of the four comparisons and determines the relevant time differences. These time differences are then sent to the main processor to determine the location of the pinger. The four hydrophones are carefully calibrated with each other so they have a similar response, making this comparison method viable. In addition, the automatic gain system guarantees the best possible signal to noise ratio from the hydrophones, and the high order, high Q filter reduces the noise as much as possible.

Inertial Navigation System (INS)

We custom built both the Inertial Navigation System and its associated fabricated board. Our INS provides the position of the submarine relative to the initial starting point, velocity, acceleration and orientation of the submarine. This information is derived from the data fed in by the main sensor controller board which is connected to PCB Piezoelectronics accelerometers that keep track of the current acceleration and velocity. The controller board also takes in bearing, pitch and roll measurements at a rate of 16Hz from a compass module from Precision Navigation.

Depth & Pressure Sensors

To determine the distance between the vehicle and the bottom of the lake, the AUV uses an Airmar "Smart Sensor" acoustic depth sounder. The depth sounder contains an onboard processor, and reports computed depth digitally, once per second via the MNEA 0183 protocol. Depth is determined using a single pressure sensor from Sensortec. Pressure data is gathered from the sensor through the main sensor board.

Motor Control

There are many techniques for driving DC brush motors at variable speeds. The simplest is to use a series variable resister. Though effective, this method is inefficient because of power wasted in the resistor. Pulse width modulation (PWM) is the industry standard method for controlling DC brush motors. It varies the duty cycle of a pulsed signal to the motor. The average power determines the motor speed. We chose Novak Super Rooster speed controllers that are designed for use with remote control cars.

The Super Rooster's low cost and high performance makes it superior to many industry controllers. The controller can operate on 12 volts, drive a maximum forward transient current of 320 amps, and is thermally protected. In addition, it is easily converted to radio control drive, making it possible to test the submarine with RC control. These controllers are controlled with a periodic pulse every 20ms. The pulse width varies in length from 1 ms to 2 ms, giving a full range of speeds from full reverse to full forward.

The final microcontroller design is built on a custom PCB board manufactured by ExpressPcb. A custom PCB design such as this one has better durability and lower noise than wire wrap or bread board implementations. This custom hardware board takes serial data from the computer and converts it into control signals for the speed controllers. The board uses an Atmel 8515 micro-controller to communicate with the main processor and generate the control signals. It has optical isolators to isolate the power system driving the motors from the computer power system. These isolators are necessary because the large switching currents of the PWM controllers generate noise on the power supply.

The custom controller also implements two safety features. It has a heartbeat feature that checks for motor updates from the main computer exactly once a second. If it does not receive any updates, it assumes the computer has failed and shuts down the motors. In addition, it has an radio controlled kill switch. If the AUV loses control, a RC controller can be used to shut down the motors.

Computer System

The onboard computer for the submarine is a VersaLogic VSBC-6 single board computer in the compact EBX form factor (5.75"x8") with 128 Mb of SDRAM and a 400Mhz AMD K6-2 processor. It includes includes onboard SVGA video chipset, 10BaseT ethernet adapter, IDE disk controllers, a PC104+ expansion slot, four serial ports, and one parallel port. The board operates on 12V and 5V inputs and draws less power than a typical motherboard.

The PC104 Plus expansion slot contains a PC104+ to PCI adapter card, which enables us to use an off-the-shelf PCI framegrabber for the operation of the vision system. It also has the added advantage of allowing us to test the entire vision system on any standard personal computer simply by using the same framegrabber.

Software Suite Overview

Operating System (OS)

The OS chosen is the Linux operating system with the RT-Linux 2.3 real-time kernel patches. We chose Linux for its stability, low resource utilization, and well-developed software development environment. We decided to use the real-time version of Linux because it alone would allow us to guarantee that low-level functions such as processing for the INS and motion planning would operate at peak efficiency in the presence of processor-intensive image and sonar computations.

Inter-Process Communication

In order to keep everything as modular as possible and facilitate rapid development, virtually every important task is in its own process – motor control, INS, AI core, sonar, and vision. Every process sends its own state over a serial protocol. Real-time processes implemented as kernel modules, for example the INS, simply write the contents of an array of state variables such as position, velocity, and orientation to real-time FIFO's. Other processes, real time or not, can read this data out by opening a block device (e.g. /dev/ins_out). Similarly, non-real-time processes such as AI core, sonar, and vision use Unix domain sockets to export their current state.

Core AI

The AI process determines the high level plan that the AUV follows. At each invocation of its main loop, it gathers information about vehicle status from all of the sensors and follows a heuristic process to either create a new motion plan or continue with the current approach.

Motion Planning

To determine where the AUV will move the algorithm keeps a record of all of the reports from the vision and hydrophone processes. By knowing the theoretical rate of drift of the inertial navigation system, the algorithm can appropriately increase the variance of old readings. Using statistical methods, it computes the most likely position of the target given the accumulated data. Since this process requires computation that is not strictly time bounded, and may require dynamic memory allocation, it is implemented as a standard Linux process. The execution of this process is not critical to the safety of the vehicle.

Hydrophone Array

The sonar process computes the time difference between the pings reaching each of the four hydrophones, and from these differences computes the relative location of the sound source. This process monitors the serial port for messages sent by the hydrophones.

After receiving a message from the hydrophones, the sonar process performs convulusion on pairs of channels of the sound data and finds the time differences. Immediately after data is received from the hydrophones, the sonar process records a timestamp for the computation of ping period. Combined with the geometry of the hydrophone array, three computed time differences fully describe the orientation of the sound source with respect to the vehicle. Using a generated system of equations, the sonar process computes the location of the beacon in three dimensions along with the approximate distance to the sound source.

Ring Detection

Ring Detection Algorithm

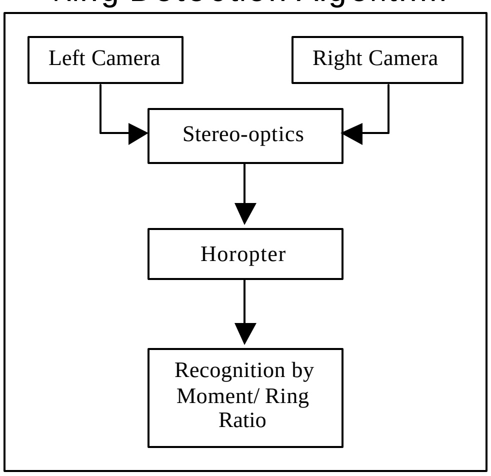

Figure 3: Ring Detection Algorithm

The video pipeline shown on the left indicates the particular sequence that we perform on the initial left and right images of the camera to recognise a ring. The two images go through three processes, namely *stereo-optics* to obtain depth information through image disparities of the two images; *horopter* to limit the search range to a certain distance (thus achieving the necessary foreground distinction from background); and *recognition by moment and ring ratio* to recognise the presence of the ring in a potentially complex environment.

At the end of this chain of processes, information about the presence of a ring in the field of vision of the camera can be reliably obtained together with relative position of this ring with respect to the current position of the submarine.

Detection of any obstacle that may get into the way of our submarine is also performed using this video pipeline through the use of the stereo-optics module.

Ring Images Before and After Horopter Procedure

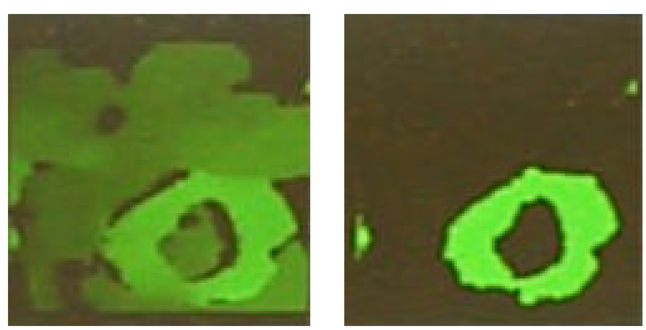

Figure 3: Left: the image after the Stereo-optics procedure.
Right: the image after the Horopter procedure.

Position Determination

The current position and bearing of the submarine is determined by combining several pieces of information, namely the depth from the bottom of the lake, the orientation of the AUV, and the current position given by the inertial navigation system. Knowing the proximity of the bottom to the AUV is critical to preventing contact with the lake bottom. The depth sounder is accessed through a controller attached to the parallel port of the main computer. The orientation of the submarine is measured by monitoring the output of the compass module. Parsing of the compass data is performed in the same manner as the depth data, insuring that stale information is cleared from the buffer at every read.

The Inertial Navigation System operates as a real time process (implemented as a kernel module), providing estimates of current position, velocity, acceleration, and orientation at regular, guaranteed intervals. It reads the data from two serial ports: the 3-degree-of-freedom compass and from a board that interfaces with three accelerometers. Acceleration and velocity are repeatedly summed between 10 and 50 times per second along with their empirically determined statistical variances. Where available, absolute data, such as depth, is integrated using the Kalman filter.

The main sensor controller board supplies acceleration, temperature, pressure, and retrieval device status to the main computer. Since time critical computation must be performed on the readings from the board's three accelerometers, the INS software is implemented as a real-time kernel module. The INS module sends a "go" signal to the main sensor board and receives a stream of data from each of the sensors in sequence. By integrating acceleration readings, the INS process can determine velocity vectors for the vehicle. By combining this data with that from the compass module, the process computes estimates of the relative position, velocity, acceleration of the vehicle.

Motor Control

The AUV communicates with its thrusters via a custom designed motor control board. This board translates serial commands into standard radio control pulse signals that can be interpreted by the Novak motor controllers. The motor control kernel module reads the contents of the INS process and extracts displacement and orientation information. This state is output as a single byte to the serial port in a binary format where the most significant five bits represent the motor power setting and the least significant three bits indicate which motor to set. Every tenth of a second up to five of these control bytes are sent updating the power settings of the five thrusters.

The motor controller attempts to adhere to the path specified by the motion-planning module. If the controller detects severe divergence from the planned path, or that unreasonable levels of thrust are needed to adhere to the path, it will report an error message to the AI and trigger the plotting of a new path.

Conclusion

The members of the Cornell University AUV Team have worked extremely hard to construct a vehicle that will successfully navigate this year's AUVSI competition. Our vehicle is a highly survivable, maneuverable platform that incorporates a high-tech computer, state-of-the-art sensor systems, and a truly artificially intelligent software suite. The combination of these features results in an AUV that is more than capable of completing the competition's mission.

The technology represented by this vehicle also holds great potential for real-world applications of artificial intelligence and the use of autonomous vehicles to perform difficult or dangerous tasks in remote environments. We look to achieve great success both in this year's competition and in the future and are thankful for the opportunities it has afforded us.

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