B.R.A.I.N. 2001 – Improvements and Innovation

BIG RED ARTIFICIAL INTELLIGENCE NAVIGATOR

AUV 2001
CORNELL UNIVERSITY

Aaron Birkland, James Buescher, Walter Chang, Hubert Chao, Richard Chung, Brian Dunstan, Vikash Goel, Scott Hartranft, Dave Hays, Wei-Chang Huang, Lars Kalnajs, Nidhi Kalra, Jeremy Kubica, Marla Leahy, John Riley, Keisuke Nakagawa, Anthony Peng, Warwick Tucker, Dan Weaver, Tony Webber, Sean Welch, Renaldi Winoto.

Cornell University
BRAIN Team c/o James Buescher
455 Rhodes Hall, Ithaca, NY 14853

Abstract

The 2001 Big Red Artificial Intelligence Navigator is an autonomous underwater vehicle (AUV) constructed for participation in AUVSI's 4th International Autonomous Underwater Vehicle Competition. The main goals of the competition are to autonomously locate and retrieve a target object using acoustic and visual cues attached to the target, to locate an array of man-made objects and determine the depth of the shallowest object in that array.

The vehicle has been completely redesigned and rebuilt from last year's entry, focused on creating robust and reliable solutions to the problems encountered during the 3rd annual competition, while improving also on those aspects of the 2000 vehicle that were the most successful. Onboard are: a modular signal-and-power infrastructure that allows rapid addition, removal, or substitution of sensor boards; hot-swappable batteries that extend the theoretical computer uptime indefinitely; an isolated motor control hull to prevent computer interference and improve thermal behavior; and a digital signal processor for hydrophone data. Combining these improvements with machine vision algorithms and reliable proportional-integral-derivative (PID) motor control, the vehicle will be in a position to successfully complete all mission objectives.

Introduction

The 4th International Autonomous Underwater Vehicle Competition is to be held in Annapolis, Maryland on July 11-15, 2001. The goal of the competition is to perform a realistic underwater mission under autonomous control. This year's mission adds the component of mapping the bathymetry of a set of objects placed on the lake floor to last year's task—retrieving a man made object. The Cornell University AUV team has completely redesigned its entry from the 3rd International Autonomous Underwater Vehicle Competition to perform the new mission. During a 30-minute time slot, the vehicle will pass through a validation gate and then determine the bearing to an acoustic beacon. Upon establishing the relative position of the acoustic beacon, the submarine will proceed towards it, guided by an optical beacon in the final approach. After reaching the beacon, the AUV will recover a man-made marker and determine the direction to an array of boxes. It will then traverse over the boxes, identify the shallowest box, and finally return to the staring position. The submarine will be completely under autonomous control, using onboard sensors to determine the positions of the objectives and the submarine's current position.

To achieve this goal, the design and construction of the submarine have been divided into four categories. The 'hull and propulsion group' is responsible for the mechanical systems on the submarine and the integrity of the hull. The 'infrastructure group' created the interfaces between the electrical and mechanical systems and designed the internal features of the hull. The 'sensors group' developed a system for detecting the beacons and monitoring the submarine's position in the arena. Finally, the 'artificial intelligence' group's responsibility was to select the appropriate computer hardware and write the computer program that controls the overall functioning of the submarine.

Design Overview

Before design of the submarine commenced, the team developed a strategy for completing the mission. This allowed the selection of appropriate hardware to complete the task with minimal complexity. The team determined that the vehicle had to meet the following criteria:

- Fit in a box six feet long, three feet wide, and two feet deep, weighing less than 100 kilograms.
- Autonomously submerge and pass through a validation gate 3 meters wide.
- Detect and accurately locate an ultrasonic beacon from long range.
- Move in three dimensions at reasonable speed.
- Visually detect a strobe light in turbid water.
- Visually locate a recovery marker and retrieve it.
- Detect a specific array of boxes and record the depth of the shallowest box in that array.
- Determine the position of the submarine relative to the starting position with sufficient accuracy to return to the starting position.

In addition to these specifications, the submarine must withstand the rigors of the competition and extended hours of testing. It was decided early in the design process that robustness was critical to the success of the project and has been the primary design goal. The major flaw in most entries to the 2000 competition was a lack of system robustness that led to catastrophic failures in vital components. The focus of this year's development was to achieve system robustness through modularity, redundancy and ruggedness:

- Modularity: Partitioning the vehicle into specific modules allows design specialization, ease of fault finding, increased field serviceability and most importantly the ability to modify or replace a specific module without a complete system overhaul.
- Redundancy: Each of the modules in the system has a functionally identical replacement on hand to allow quick replacement and easier fault-finding. For some critical components, redundant modules may be simultaneously installed to allow real-time replacement in the case of a malfunction.
- Ruggedness: Where proven suitable, off-the-shelf products have been integrated in preference to custom-built parts because they generally offer greater reliability. Many of the submarine's components, such as the cooling system, are purposely over-engineered for worst-case scenarios to minimize the probability of failure.

These factors have been integrated into all parts of the submarine to ensure proper performance under the non-ideal conditions expected at the competition.

Control Systems and Mission Strategy

Computer Hardware

The submarine uses a Versalogic VSBC-6 single-board computer with a Pentium class processor running Linux with some minor in-house modifications. Machine vision is achieved using a Sensoray model 311 frame-grabber that provides a standard Brooktree/Connexant Bt848 capture chip in a PC104+ form factor. The use of commonly available off-the-shelf hardware enables us to do most testing and development on ordinary desktop computers without undue concern for hardware or software compatibility.

High-level Control Code

The higher level processing is achieved by a central routine written in C++. The main program consists of two forked processes; the child process carries out the mission, and the parent keeps track of elapsed time, and periodically reminds the child to update its sensor readings, dead reckoning and other processes. If the mission is completed within the assigned time frame, the child kills the parent and the main program terminates. If the assigned time is up before the mission is completed, the parent kills the child and the main program terminates. The child program divides the mission into the following phases depending on the current task:

- PHASE_INIT: A timer is started and all sensors are updated. This ensures that the submarine can commence its dead reckoning.

- PHASE_GATE: First, the vehicle dives to a shallow depth, turns to face the validation gate, and passes through it.
- PHASE_HYDRO: At this stage, the process waits for the hydrophones to detect a ping from the acoustic beacon. After registering a ping, the submarine starts moving towards the beacon using additional pings for course corrections. Once the submarine has passed over the beacon, the computed bearing will shift by 180 degrees. When such an event is detected, the vehicle halts, turns around 180 degrees, and dives to a small distance above the lake floor.
- PHASE_GRAB: Hovering over the lake floor, the submarine waits for the photodiodes to pick up the strobe flash and rotates until a flash is detected. Upon detecting a flash, the submarine heads towards the beacon, correcting its course with subsequent flashes. When strobe flashes are no longer detected, the beacon has been passed. If the marker is recovered, the submarine continues to the next phase; otherwise it repeats the current phase until the marker is recovered.
- PHASE_FIND_BOXES: After recovering the marker the submarine travels away from the beacon in the opposite direction from the boxes. It then reacquires the beacon and uses this bearing to guide the submarine to the start of the boxes. The vision will then signal when the array appears on screen, which causes the submarine to stop.
- PHASE_FOLLOW_BOXES: Once the boxes have been found, they are followed using the downward looking camera and the depth-sounder array. The absolute depth of the boxes is calculated using the depth sounder and the pressure sensor, and the shallowest depth is noted.
- PHASE_RETURN: Using the MAP class, which has been maintaining a dead reckoning of our position, a return bearing can be calculated. The submarine follows this bearing to the starting position.
- PHASE_COMPLETE: The submarine stops and surfaces, halting the mission program.

Mechanical Systems

Hull

The vehicle is structurally oriented about an open-frame welded-aluminum support structure, to which all components are mounted. This approach is sturdy and durable while being almost infinitely flexible during the integration of externally mounted vehicle systems. While the key propulsion components are constrained to various locations by the need for complete dynamic control, almost every other component of the vehicle may be relocated to accommodate changes in the AUV's external hardware or mission profile. In addition to providing excellent configuration flexibility for meeting the mission requirements, the physical modularity of the submarine also guarantees that all components are quickly and easily removable for repair or replacement.

The main electronics hull is comprised of lightweight, 8-inch diameter PVC pipe. The pipe supports an internal system rack that holds the AUV's modular signal distribution harness and all of the individual component boards. This rack keys into the main hull and aligns blindly to seat a back plane connector. This connector completes all internal-to-external signals and power routing for the internal electronics. The main hull (see Figures 1 and 2) is supported by a series of cradles affixed to the central frame and is secured by four easily adjustable and quickly releasable webbing straps.

Figure 1 – A forward/side view of the vehicle. Note the aluminum thermal endcap.

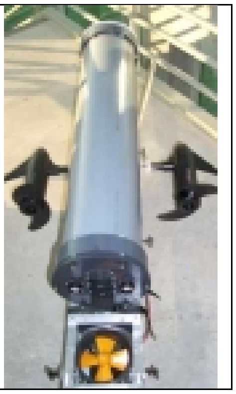

Figure 2 – A downward view of the vehicle.

Power for the entire submarine is provided by a series of interchangeable battery racks. Each aluminum rack contains five sealed batteries. These racks are entirely self-contained and may be changed as single units. The racks are fastened to the underside of the central frame by a set of four spring-locking pins, allowing extremely rapid and simple switching of the batteries.

The team was confronted with the conflicting needs to satisfy a physical size requirement without hindering the capability of the submarine's long-range passive acoustic hydrophone array. This year's vehicle employs an articulated boom system to deploy the AUV's hydrophone array once the vehicle has entered the mission arena. The hydrophone array consists of four 26-inch long fiberglass booms that are driven by heavily geared and sealed 12VDC electric motors through a simple jackscrew system, which respond to commands sent by the central computer. Deployed, the arms form a planar array that is approximately 60 inches square. In the folded position, the booms tuck alongside the central frame and fit completely within the specified dimensional box. In the interest of reliability, the array and its actuators are also easily serviceable, and designed to be quickly replaced if a problem should arise.

In addition to a robust and highly modular design, safety is a primary concern. A physical external kill switch immediately disengages the thrusters from their supply battery. Alternately a remote-control kill switch can remotely disable the thrusters. Engaging the vehicle-based external kill switch also deploys an emergency air bladder (see Figure 3) that renders the AUV positively buoyant. This facilitates easy recovery in the event of a serious malfunction. This system is powered by a carbon dioxide cartridge that can be armed immediately before the vehicle is deployed.

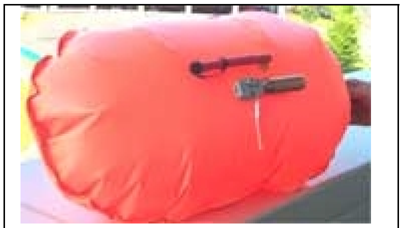

Figure 3 – Emergency Air Bladder

Propulsion

Control of forward and reverse locomotion and orientation about the yaw axis is achieved with two laterally mounted Minn-Kota trawling motors. The vehicle is neutrally buoyant and changes in depth are made using vertical thrusters. The two vertical thrusters were salvaged from a commercial Hyball ROV. The propulsion system has complete electrical isolation from the vehicle's other electrical systems, and draws power from a separate battery bank. The motors are controlled using four Novak Super Rooster pulse width modulated (PWM) speed controllers. These were chosen for two reasons: they are the cheapest, most readily-available speed controllers that allow for easy replacement in case of failure, and they accept PWM signals directly from a commercial radio control unit. These motor controllers have 64 discrete speed settings and good thermal dissipation. An eight-channel Scott Edwards Electronics Mini SSC-II serial-to-PWM controller is used to operate the speed controllers. An operator retains the option of remotely switching from computer control to remote control using a High Sky universal switch-controlled relay bank. This feature is useful in the development phase, as it allows remote over-ride in the case of a computer or motor controller failure and provides a soft kill feature.

Computer control is achieved over a serial interface with the Mini SSC-II. The feedback control portion of the motor control system is a proportional-integral-derivative (PID) controller written in C++. PID control is sufficient—the submarine is dynamically stable and will remain on its current path if left alone.

The controller is a process that runs on the main computer. It reads the current, last, and desired parameters from shared memory, and sends the required speed settings to the speed controllers via the Mini SSC-II. The current algorithm only requires the current and last set of measurements to function. It keeps a running total of the error for each parameter for the integral control.

The output from the vertical thrusters is calculated by the depth PID control algorithm. The submarine is designed to be dynamically pitch stable, allowing a common output to be relayed to both vertical depth controlling vertical thrusters. The outputs for the primary thrusters are calculated in two steps. First, the velocity PID controller calculates a base value to be sent for both main thrusters. These outputs are then increased or decreased by a factor determined by the heading PID control algorithm to achieve directional control

Thermal Management

Overheating was one of the main reasons for the high rate of system failure during the 2000 competition. The internal temperatures inside last year's hull exceeded 55 degrees centigrade during extended operation. To minimize this problem, this year's design includes internal fans to equalize the temperature throughout the hull and an active thermal endcap. This device transports the heat out of the hull using an active cooling sandwich consisting of three Peltier junctions capable of transferring 180 watts of heat. To reduce the amount of heat being generated within the hull, the speed controllers have been moved to a thermally conductive aluminum hull that is externally mounted. This dissipates any excess heat into the surrounding water.

Sensor Systems

Hydrophones

The most crucial capability of the sensor system is to locate the target beacon. This is achieved using a passive hydrophone array. Cetacean Research, Inc. produces the four hydrophones. These omni-directional hydrophones come equipped with a built-in preamplifier inside the plastic encapsulation and provide a uniform -165 dB sensitivity. The hydrophones are mounted in a rectangular configuration on extendable booms to maximize the difference in arrival time for the beacon pings (see Figure 4). This reduces the dilution of precision for the bearing calculated from the time differences. The signals from the hydrophones are passed through an analogue front-end, and digitized by a dedicated digital signal processor (DSP). The DSP applies an equi-ripple FIR filter to the signal to isolate the 27KHz component of the signal and calculates the time differences through a discrete cross-correlation. The analog front-end preconditions the signal before being sampled by the analog-to-digital converter (ADC). The analog circuitry amplifies the signal from the hydrophone to take maximum advantage of the ADC's dynamic range.

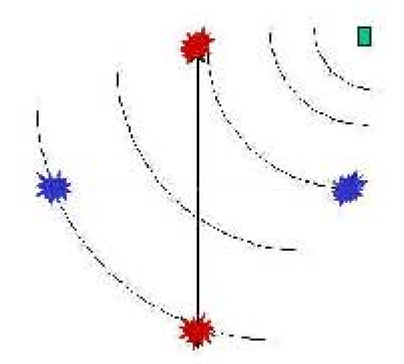

Figure 4 – Acoustic ping reaches hydrophones at different times

The ADC is a Texas Instruments THS1206, capable of simultaneously sampling four analog signals at 1.5 million samples per second with a 12-bit resolution. It employs an internal 12-word (12-bit each) FIFO register, significantly increasing the throughput achievable by the controlling DSP. The conversion clock is provided by the DSP.

The Digital Signal Processor chosen for the task is a Texas Instruments TMS320C6711. The digital signal processing hardware is mounted on a standard C6711 DSP Starter Kit (DSK). The DSK board contains the DSP itself with expansion memory and flash memory, giving it stand-alone operation capability. The DSP system communicates with the submarine's computer over a serial interface with the aid of a Maxim serial line driver. The hydrophone system returns three time differences to the computer; from these, the angle to the beacon is calculated.

Due to the modularity of the system architecture, it was possible to develop two parallel signal-processing systems for the hydrophones. Along with the digital approach, an analog system was developed using a four-channel, four-stage active band-pass filter centered on the 27kHZ beacon frequency. The output from the band-pass filter is rectified and then compared to a voltage reference to detect the rising edge of the beacon ping. The time differences are calculated using an ATMEL micro-controller. This approach is functionally equivalent to the digital approach. The module takes in four analog hydrophone signals and returns three time differences. This allows the two modules to be swapped without making any other changes to the system.

Navigation System

Several different options were considered for the navigation system. An adequate navigation system enables the submarine to calculate its position with sufficient accuracy to return to the starting position. Unlike other components of the submarine, the major consideration for the navigation system was cost. There are several systems capable of more than adequate accuracy, such as Doppler velocity logs (DVLs) or inertial guidance systems, but the cost for such systems is upwards of $10,000. The eventual choice was a dead reckoning system that integrates heading and speed over time to determine the vehicle's position. Additionally, there are three ultrasonic depth sounders and a pressure sensor to determine both altitude above the stream floor and depth below the surface. A Precision Navigation TCM2 compass establishes heading, and a Sensotec fluid pressure transducer measures the vehicle's depth below the surface. The Corus commercial integrated yacht instrument from Simrad provides velocity, depth and auxiliary compass data.

As with all the systems in the submarine, the navigation system is highly modularized. Each unit (depth, speed, and heading) is a standalone device mounted on a separate board, communicating over a 76,800-baud data bus. This data bus is then converted to an NMEA 0183 signal. The three separate NMEA signals are multiplexed together using a NoLand N183-4 four-channel serial multiplexer. The multiplexer feeds the computer the current speed depth and heading via a serial line driver to a serial port.

To aid in determining when the submarine is over the array of boxes, the vehicle is equipped with three depth-sounder heads to give a stream-bottom profile. The three depth sounder heads are multiplexed into one driver using a pair of analog multiplexers. The computer selects which sensor to connect to the Corus system over the same serial line used by the NMEA multiplexer. Data from the sensors is used to correct the record of the submarine's position on an internal map using Monte Carlo localization.

Vision

The camera system consists of two CCTV underwater color NTSC cameras connected to the PC-104 frame-grabber. The output of both cameras is captured at 640x480 pixel resolution. Each camera is equipped with an array of LED's that can be turned on and off by the computer. This enables the vision system to compare the same scene under different illumination conditions in a short span of time.

One camera is mounted alongside the depth sounder array, pointed downward. Its goal is to attempt a visual detection of the man-made objects by one of two methods, depending on the water conditions. The first method takes advantage of the reflective level surface on the top of the array of objects. It interprets a bright highlight as the top of one of the objects. Because the camera adjusts its output to average illumination level, bright reflective highlights accompany a much lower average illumination in the digitized image. The highlights can be detected using a threshold to convert the raw image into a binary one, then using a flood-fill of adjacent pixels to identify the largest continuous area. The second method, likely to be more successful with an object raised several feet from the bed of a brackish stream, is to scan the image for the largest white rectangle and to interpret it as the top of the object.

The second camera performs the more complex task of tracking the recovery marker. This is accomplished by edge detection of the 1" shaft of the marker. After using a very strong gaussian blur, the top and bottom discs of the marker are detected as blobs. At ranges of approximately a meter or two, depending on illumination conditions, the use of the camera's LEDs may permit tracking by surface highlight as described above.

Depending on water conditions, the AUV's main LED lamps may be used at longer range.

Light Sensors

To supplement the machine vision system, the vehicle is equipped with an array of 16 photo-diodes. The array provides an approximate bearing to the optical beacon. The photodiode outputs are multiplexed together and then digitized. The digitized signals are compared against one another to find a relative maximum, which indicates an estimated bearing to the beacon. This bearing, relative to the orientation of the submarine is passed to the computer over a serial line. This system provides a simpler, but less precise backup to the vision system and to the sonar at close range.

Infrastructure

Internal Wiring

The heart of the infrastructure is the electrical design of the submarine interior. Last year, individual board designers created separate interconnect standards, resulting in a variety of different board sizes, connectors, and power supply values. The new system has three major components that help resolve these issues.

The first component is an internal back plane system, with an associated wiring harness. In the place of haphazard connections between systems, sensor boards are mounted using a common standard. A 120-pin DIN connector is used to mount a board to the back plane. This connector delivers power, serial ports to communicate with the computer subsystem, and signals for communication outside the hull.

The back plane system provides two connectors per connector board, one on either side of the internal aluminum mounting tray. For maximum flexibility, the boards can be mounted on either side of the rack, and in any location within the submarine that has an appropriate connector. The back plane system described has several major advantages. It provides a simple, consistent interface to all designs, contributing fewer possible points of error and a much simpler debugging system. It also provides a much better thermal solution, as the signal and power lines are routed beneath the sensors boards, leaving the top open for airflow.

The back planes and sensors boards are all mounted to a single removable internal tray. Connections that must pass outside the hull are constrained to a single permanently attached end-cap. In order to make a good electrical connection between the tray electronics and the end-cap connectors, a blind mounting system was required. This was achieved using two 120-pin rack and panel connectors. The two connectors provide all the connections between the end-cap and the internal tray, including power, ordinary signals, and sensitive signals such as hydrophone and video camera inputs.

The endcap is a circular piece of PVC that seals over the PVC hull to provide a watertight seal. All connections are made through the single endcap, through five connectors. Of these five connectors, three are 35-pin weather-resistant sealed connectors from AMP, providing a total of 105 external signal connections for the entire submarine. The signal wires emerge from the sealed endcap connect through waterproof connectors to the appropriate sensor. This permits a semi-permanent mounting of most of the sensor systems onto the hull, greatly reducing the clutter due to external wires.

Power Distribution

Last year, a major problem with the design was power distribution. In order to avoid having to power down the electronics the current design has three separate, identical power connectors. Two power connectors are in the rear endcap and a single mount on the interior rack. Any combination of these connectors may be used without danger, providing hot-swap capability. This makes it possible to either switch battery packs during operation, or to attach a power input to the open side before removing the tray. The vehicle can move from active water operations to a bench test configuration without powering down the system at all.

Last year's power distribution system was hampered by an inefficient and therefor hot power supply. In order to solve this problem a more efficient switching power supply has been designed. By increasing the overall efficiency, both power consumption and heat generation have been reduced.

The improvements to the infrastructure system are designed to standardize and simplify the interconnections between subsystems both inside and outside of the hull. Thus, the overall debugging time should be reduced, and the system should have enough flexibility to meet requirements for not only this year, but also years to come.

Conclusion

Cornell's entry into this year's International Autonomous Underwater Vehicle Competition is a redesigned and improved vehicle evolved from last year's entry. Major improvements made in the reliability and sophistication of the overall system include:

- Optimized hull and propulsion systems
- Redesigned signal and power infrastructure
- Digital hydrophone data processing
- Effective thermal management
- More accurate navigation and propulsion systems

The vehicle shows great potential for success at this year's competition.

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