Hammerhead: Autonomous Underwater Vehicle

Daniel Bryant, Chris Crutchfield, Nick Gurtler, Chris LaFlash, Karl Schulze

Amador Valley High School Robotics
2426 Crestline Rd.
Pleasanton, CA 94566
(925) 485-7890 Email: karl.s@home.com

ABSTRACT

Hammerhead is an autonomous underwater vehicle, designed and built for the Third Annual International Autonomous Underwater Vehicle competition. Created by a team of high school students with limited resources and experience, this vehicle is the product of several months of intense work.

The Hammerhead platform is designed to give reliable shallow-water operation and is modularly constructed to facilitate servicing and parallel development. Four motors, capable of 30 lbs of thrust apiece, drive the sub, and allow for full pitch and yaw control. When completely assembled, the vehicle has a mass of 98 kg and is approximately 2% buoyant. The total length is 6'4", with a diameter of 11". It can reach a top speed of 0.8 m/s and has been tested down to 20 feet depth.

The on-board computer, running Linux, uses data from four Hydrophones to locate the target beacon. It navigates toward the ping, and then switches to a digital camera once within range. Using the known specifications for the recovery loop, the sub tracks the loop, picks it up with an attached hook, and returns to the surface.

The software systems were developed in parallel with the hardware platform and can be tested using a custom-built simulator. All of the systems are designed in a modular fashion to permit easy modification and to facilitate cross-platform testing of the code. This strategy has permitted us to use a rapid development cycle, which gives us the opportunity to test and refine both the software and hardware platforms.

The Challenge

The Autonomous Underwater Vehicle Competition presents a variety of engineering challenges that Hammerhead has been designed to meet. The high-level goal of the mission is to locate an acoustic beacon in a test pond and then retrieve a recovery marker near the location of the beacon. The sub must perform this mission completely autonomously and should calculate the ping rate of the beacon and the flash rate of an associated Xenon flash bulb.

To meet this challenge, our team researched previous teams' designs and developed a hybrid design, using components, such as the engines and the compass, which had been proven in the field. Consideration was also taken to simplify the construction process, as the limited accuracy of our machining tools could make assembly of parts difficult. With this in mind, we chose to use a rather large design (6'4" in length), which is more forgiving to manufacturing errors.

Hull Design

The outer hull is constructed from two 10" tubes of PVC pipe, including a bell near the forward end that allows the two sections to connect. At the ends of the pipe are additional 10" tubes, mounted vertically. These tubes are feathered to the main tube with resin and serve as shrouds for the vertical thrusters. The main body tube is capped with two sealed bulkheads. The ends are filled with foam, forming a cavity between the bulkheads and the vertical thruster shrouds. The wires for the motors are run through the bulkheads and through-bolts are used to strengthen the connection between the main body tube and vertical shrouds.

The engines are four Minnkota Endura 30 Trolling Motors, chosen for their reliability and low noise output while running. Two motors are located in the vertical shrouds and mounted to the bulkhead. In addition, they are attached to the shrouds with aluminum brackets to keep vibrations under control. These engines are used to control the depth of the sub and to keep a stable pitch. This design was chosen for its simplicity, as the proper design of a ballast system

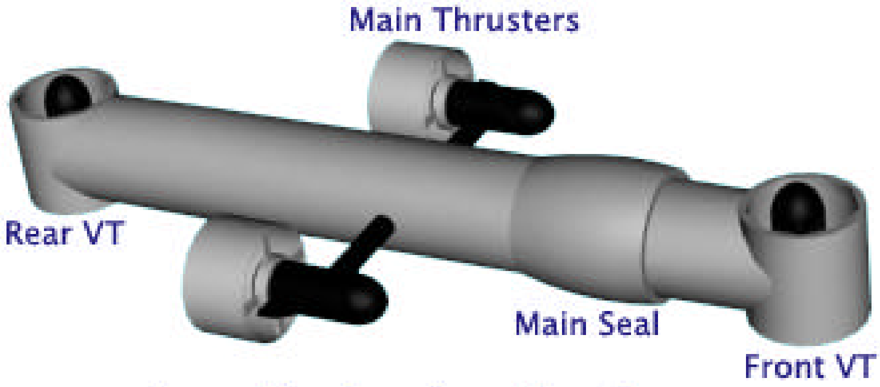


Figure 1.1 – Overview of Exterior

requires greater precision.

The remaining two motors are attached to PVC blocks, sanded to match the body tube curvature, and then held in place with four hose clamps. These main engines provide control of forward motion and allow for sharp and/or high-speed turning by running the engines at various speeds. Because of the design, it is possible for the sub to stop completely and perform a 360-degree turn. Copper braces are used to reinforce the engines and stabilize their vibrations and the entire assembly is sealed with epoxy and silicone rubber.

On the underside of the main body, a PVC valve assembly is mounted to the main tube and attached with PVC glue. The end is threaded, enabling the attachment of a pressure valve, so that we can pressurize the interior for leak testing. It also provides the needed pressure release to permit mating and separating of the two ends of the body.

Proper mating is facilitated by an alignment pin, which goes through blocks of PVC that have been sanded down and glued to the body. Once mated, holes on the two ends of the body pipe are lined up and pins are inserted to keep the body tubes from slipping. The use of pins allows the body to be taken apart quickly, which is a definite improvement over our original method of using bolts. When the two ends are mated, the watertight seal is provided by two well-lubricated o-rings.

Other external components, including the camera and the velocity sensor, had to be mounted on the exterior. However, it was also necessary for these components to have an electrical connection to the interior. We considered using waterproof electrical connectors, but instead used flexible tubing, with waterproof mating points on the hull and the component to be connected. This provides an effective seal, but also enables the sub to be disassembled for shipping.

Internal Rack Mount

All of the internal components are attached to a rack mount system,

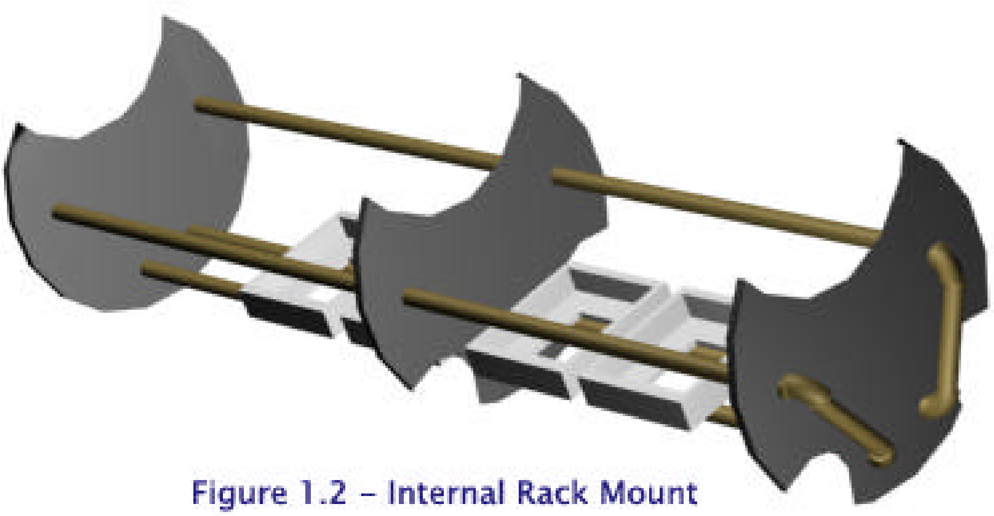


Figure 1.2 – Internal Rack Mount

created from copper piping and circular sheets of PVC. The PVC adds structure to the piping and allows it to support the batteries and other components. The assembly slides into the tube and then aligns with two blocks fitted with screws. The mount is then secured with wing nuts, insuring that the interior rack is aligned properly. Also, the front sheet is used as a mounting location for all the external wires that attach to the interior system. This way, removal of the electronics for servicing is as simple as unplugging the cables, undoing the wing nuts, and sliding out the entire rack mount.

The copper piping in the rack mount is also used for cooling. Water from the exterior is actively pumped through the system using an inline 500 gal/hr bilge pump, chosen for its price and accessibility. Heat sinks are attached to important components, including the computer power converter and speed controllers. In addition, fans are used to circulate heat throughout the sub, allowing it to radiate out both through the cooling system and the hull. The interior is also mounted with temperature sensors (LM-35) that alert the onboard computer to any possible overheating.

On the bottom of the rack mount are several sponges, attached with twist ties. These are designed to provide water tolerance by absorbing water that runs to the bottom, thus preventing splashing. This allows the sub to continue running for the length of the mission if any small leaks develop. In addition, all of the expensive electronics are mounted in watertight boxes; this provides a second level of protection should the interior ever take on significant water. Other protocols are used to detect larger leaks and allow us to avert such problems. Although we expect the body to be fully sealed, we nevertheless want to insure the electronics remain protected.

On top of the bottom pipes are sliding aluminum mounts for the batteries. The batteries are secured to the mounts using tie wraps. The slide mounts can then be tightened once the weight of the batteries is evenly distributed. The mounts are constructed from aluminum to enhance heat exchange with the copper piping.

Electrical Systems

Power for all the motors and onboard electronics is provided through four sealed 12V gel-cell security batteries. Each battery provides 18 Amp Hours for a total of 72 Amp Hours at 12V. The first three batteries are connected in parallel to a power bus. These batteries are used to power all mechanical aspects of the submarine, including the engines, fans, and cooling pump. Between every negative terminal and the power bus is a 30 amp relay with a 40 amp fuse; the fuse is conveniently located for easy replacement. All three relays for this system are normally open and tied together in parallel to the main kill switch mounted on the body of the sub. This allows for a simple and reliable method to cut power to all mechanical aspects of the vehicle.

The remaining battery is used to power the computer and other electronics. The two systems were kept separate in order to prevent a low-battery condition from shutting down the electronics. This battery also has a relay placed across its ground wire, which is attached to a secondary kill switch, also mounted on the body. The computer and electronics react poorly to an uncontrolled shutdown. By providing a separate kill switch for the motors, we can shut down the sub without harming the computer.

The computer runs the RedHat 6.2 release of Linux and uses a development kernel in order to gain access to USB drivers for the camera system. It runs off an Advantech 5864 Pentium-based Single Board Computer, running a P233 MMX processor. The system includes 128 MB of SDRAM and a 12 GB IBM Travelstar hard drive. These systems were chosen for their small size and low power requirements.

In addition to the main computer, a Motorola MC68HC912B32 micro-controller is used to control the four speed controllers, process incoming sensor data, and handle high-level speed control tasks using the compass. The compass is a TCM-2 from Precision Navigation, chosen for its accuracy and proven reliability in this competition.

For the speed controllers, we chose the Novak Super Roosters, which are both reliable and low-cost. Designed for RC cars, these controllers are rated for 300 amps forward and 150 reverse. The controllers are mounted at the front of the sub, providing easy access for calibration and verification of signals.

In order to locate the acoustic pinger, we mounted four hydrophones on the perimeter of the sub. These hydrophones are typically used to record audible underwater noises, such as whale-calls, using an above-water amplifier. We chose them for their low cost ($50 each), which is significantly less than most commercial solutions.

The signals from the hydrophones are run through a series of homemade amplification, filtering, limiting, and zero-crossing detection circuits. The output is a square wave that can be used to trigger a timer on the Motorola board, which then generates a series of time-stamps for the on-board computer. From this data, we can determine the time differences between the signal receipts and use this to generate a direction vector from the sub to the beacon.

At the bottom of the sub, a digital camera is mounted in a watertight box, which is carefully machined to allow for proper calibration. The camera, a Creative Video Blaster III, is chosen for Linux compatibility, competitive price, and frame rate. The camera is essential in the final approach to pick up the loop and it also aids in determining flash rate. To further assist in the flash rate determination, we included a simple photocell, mounted to the underside of the camera.

The sub includes a velocity sensor, which uses a 10:1 tube length to prop width ratio in order to minimize the effects of turbulence. We can then read an rpm pulse using the Motorola board's built-in pulse accumulator. While not sufficient to keep a dead-reckoning estimate of our position, it nevertheless gives enough accuracy to perform simple triangulation to determine the distance to the beacon.

An external water pressure sensor, capable of reading from 0-100 psi, is used to provide 2" depth detection accuracy. Interior sensors, capable of reading from 0-25 psi, simplify leak detection. Leaks can also be detected using a water alarm, which consists of two probes in a sponge. The depth of the pond below the sub is measured using an acoustic transmitter and the existing hydrophone system. It is crucial that we avoid the bottom, as sediment is easily kicked up by our vertical thrusters, which would impair operation of the camera.

Control Software

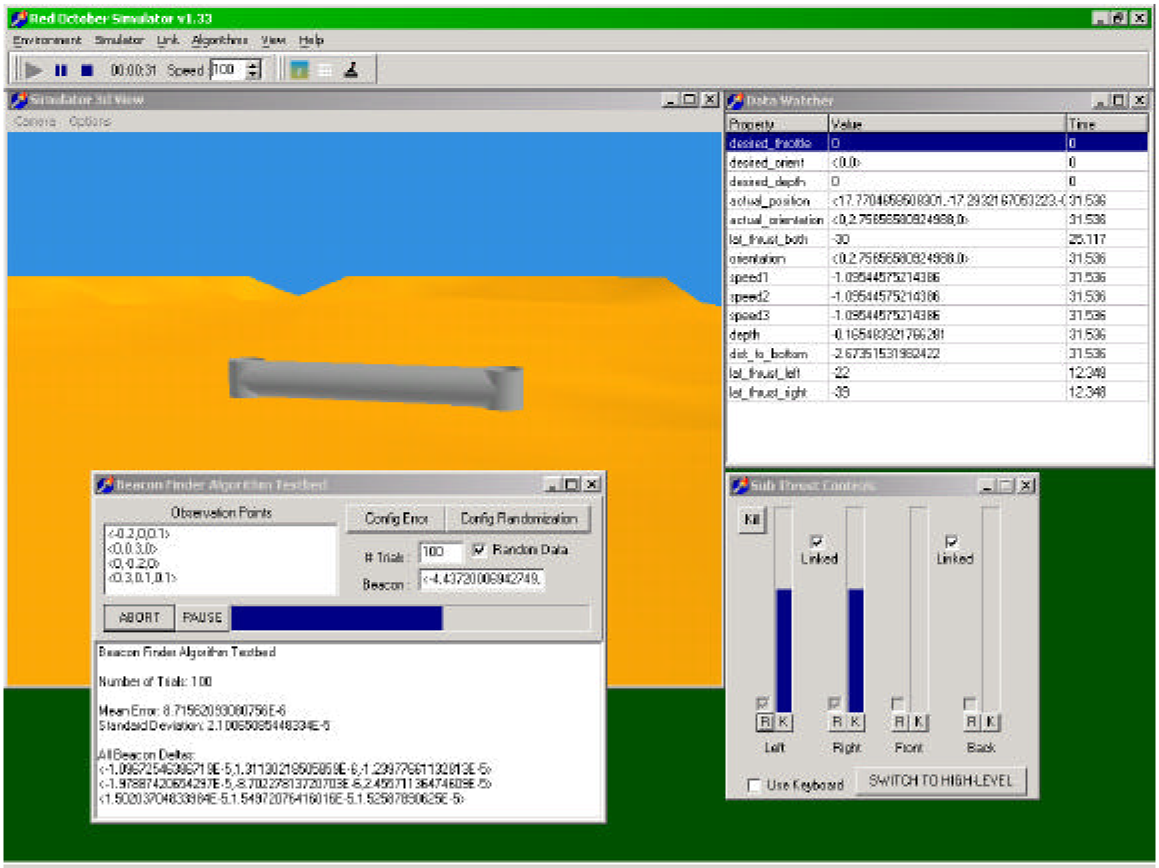
There are three levels of control software in the sub. The first layer, residing on the Motorola board, gathers information from the sensors and provides an interface with which the onboard computer can drive the motors and perform other basic tasks. The second layer runs on the onboard Linux computer and runs the high-level control code that allows the sub to be autonomous. The final layer consists of a simulator / monitor / driver system that interfaces with the sub from a land-based laptop, via either tether or wireless, to facilitate debugging.

The Motorola code is developed using a specialized C compiler that allows for quick updates the on-board EEPROM. The chip includes four channels of hardware PWM for running the speed controllers, and has eight channels of 8bit A/D inputs. It also possesses a large number of digital I/O lines. The Motorola chip is responsible for handling all of the inputs from the hydrophone circuits and manages high-level speed control functions, auto-correcting for stable pitch and desired yaw using data from the compass. All commands are sent over the serial interface using a simple ASCII protocol, allowing full driving capability from a terminal window if desired.

The on-board computer interfaces with the Motorola using the serial port and handles the high-level decision making tasks for the sub. It also receives a serial feed from the compass. However, rather than implementing a dead-reckoning estimate of our position, which would be prone to steady-state error build-up, we chose to use a dynamic response system. When locating the beacon, the sub always moves towards where the last ping says that it should be, and triangulation/distance calculations are performed whenever the sub’s motion between pings was roughly linear, minimizing error. When the sub is within a certain calibrated range, it turns on the camera and begins to look for the recovery ring.

The ring-matching algorithm is designed to work under a variety of circumstances. It first does a background sampling, and then marks all pixels that vary from the background by a certain calibrated tolerance. It then goes through the marked image and looks for holes or noise pixels, which could potentially arise from dust being stirred up from the bottom. Finally, it calculates the extents of any elliptic shape in the image, and the extents of any hole in that ellipse. Assuming that these extents are not too extreme, the values are fed into a formula that returns the position of the ring relative to the sub as well as its orientation.

The direction-finder algorithm is also extremely important. From the four hydrophones, we end up with three time deltas and information concerning the order in which the hydrophones heard the ping. From this information, it’s possible to create a cone of possible pinger locations. This is generated with a combination of two algorithms. When the pinger is sufficiently far away (according to previous ping information), we use a planar wave approximation. However, when the pinger is too close to use a planar wave, we can use a more accurate, but more jittery, approximation.



Property	Value	Time
desired_throttle	0	0
desired_orient	<0,0>	0
desired_depth	0	0
actual_position	<17.7704658508301,-17.2932167053223,(	31.536
actual_orientation	<0,2.75856580824988,0>	31.536
lat_thrust_both	-30	25.117
orientation	<0,2.75856580824988,0>	31.536
speed1	-1.09544575214386	31.536
speed2	-1.09544575214386	31.536
speed3	-1.09544575214386	31.536
depth	-0.165483921766281	31.536
dist_to_bottom	-2.67351531982422	31.536
lat_thrust_left	-22	12.348
lat_thrust_right	-39	12.348

Observation Points
<-0.2,0,0.1>
<0,0.3,0>
<0,-0.2,0>
<0.3,0.1,0.1>

Trials : 100
☑ Random Data
Beacon : <-4.43720006942749,

```
Beacon Finder Algorithm Testbed

Number of Trials: 100

Mean Error: 8.71562053080756E-6
Standard Deviation: 2.10065085448334E-5

All Beacon Deltas:
<-1.09572546386718E-5,1.31130218505859E-6,1.23977661132813E-5>
<-1.97887420654297E-5,-8.70227813720703E-6,2.45571136474609E-5>
<1.50203704833984E-5,1.54972076416016E-5,1.52587890625E-5>
```

☐ Use Keyboard

The Simulator

Because of limited time and resources, it was necessary for the software systems to be developed in parallel with the hardware platform. In order to make testing of the software feasible, a simulator was developed to allow for dry-lab testing of all the control code. In addition to incorporating algorithm-specific test-beds, the simulator, dubbed Red October, contains a variety of control functions to facilitate testing of the sub while it's in the water.

Communication with the sub is handled with UDP and multiple computers can be connected to the platform at any given time. The thrust controls, driven via joystick, can be used to drive both the virtual sub and the physical platform. Additionally, the interface provides for full monitoring of all data coming back from the sub, including camera feeds. This allows for quick response in case something goes awry and is also helpful in debugging.

The simulator was developed using Borland Delphi, chosen for its familiarity and impressive capability as a Rapid Application Development platform. All the components are developed in a modular, object-oriented fashion, both allowing for quick modification as the need arises and facilitating the possible reuse of the software system in future years. Additionally, the control code (which has to be written in C for compilation under Linux), can be loaded using a system of control DLLs that provide an interface with the Simulator. In this way, the control code only has to be written only once, in the intended language, thus preventing possible errors caused by porting of code.

Conclusion

Hammerhead is designed to be an effective solution with a minimum of frills. As first year entrants in the competition, we examined technology that had been effective in previous years and hybridized those components that would perform equally well in our platform. This process has been a long, but beneficial learning experience, which has given us a chance to take part in a wide range of disciplines. The hardware platform is essentially complete and, with the software systems well on their way, we look forward to the competition in Florida.

Acknowledgements

Special thanks goes out to Amerimade Technology, who provided us with financial and technical assistance, in addition to access to the handiwork of their amazing labs. Thanks also goes out to Wunderlich Malec Engineering, Buster McCurtain, Mike Faber, Kent Young, and Kelling Northcross & Nobriga for their generous donations. Additional thanks for Ryan Herco, who gave us an educational discount on our PVC pipe, and the many individuals who provided donations: the Drew family, the Benton family, Linda Ebright, Janet Lamarre, Velma Johnson, the Freddette family, the Bervon family, and the Everton family. We would also like to thank our parents, particularly Dieter & Christine Schulze and Harold & Greta LaFlash, who supported us with expertise, food, numerous part runs, and patience in allowing us to house a 6' long submarine in their garages. Thanks to Rob Sullivan, who provided us with assistance on the electronics and allowed us to borrow his oscilloscope; also, Chris Crosby, an EE major at University of Colorado at Denver, who gave us tips on where to find the hydrophones. Further thanks to David Vickerman and Deep Ocean Engineering, who allowed us to tour their facilities and provided helpful tips. Last, but certainly not least, we'd like to thank Jerry Shelly, who served as our club advisor, and Bud Engel, who provided us with a wide range of support.