The ORCA-1: An Autonomous Underwater Vehicle

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Abstract

We have designed and are building the ORCA-1, a fully autonomous submarine, to enter in the First Annual International Autonomous Underwater Vehicle Contest.

The vehicle is designed for efficient, high-speed, reliable operation in shallow water. It is 1.4 m long and has a mass of 48 kg. It has a hydrodynamic design and modular construction. Side-mounted thrusters are used to drive and differentially turn, and vertically mounted thrusters are used to dive and pitch. The vehicle has a slight (approx. 2%) positive buoyancy, and is held at depth by the vertical thrusters.

ORCA-1 images its surroundings using a forward-looking and a bottom-looking sonar array, and uses a compensated inertial navigation system implemented as a Kalman filter to determine its absolute position at all times. A water pressure depth sensor, a magnetic compass, a fluid inclinometer, and a set of impeller velocimeters round out the vehicle's sensor array.

ORCA-1 is powered by a 420 watt-hour sealed lead-acid gel-cell battery, and can operate at its top speed of 3 m/s for 1.5 hours on a single charge. The vehicle is controlled by an onboard 586-class computer running the Linux operating system.

We built the ORCA-1 for a relatively low cost ($5000) by modifying retail products wherever practical rather than buying OEM modules or building custom-designed systems. With our modular design and redundant sensor array we believe that we have a design for a vehicle that can accomplish the mission "Better, Cheaper, Faster."

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[1] Authors listed in alphabetical order

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Introduction and Design Overview

The International Autonomous Underwater Vehicle Competition poses an engineering challenge which our team, composed entirely of students, intends to meet. The contest arena is the P-253 test pond at the Naval Coastal Systems Station in Florida. The pond is oval in shape, 110 m by 70 m, and has a maximum depth of 12 m at the center. Six gates, with two uprights and a crossbar made of PVC pipe, will be submerged along the perimeter of the pond, along the 3 m isobath. Attached to the sixth gate is a target zone, a 3 m by 3 m raised platform of variable and irregular bathymetry, enclosed by four corner uprights. Each team’s fully autonomous underwater vehicle must pass between the uprights and under the crossbar of each gate, enter the target zone, find the point of maximum depth, release a marker beacon at that point, and surface between the target zone uprights. The vehicle is not permitted to drop navigation beacons or utilize the Global Positioning System. Points are awarded for each gate traversed, for marking the maximum depth in the target zone, for surfacing in the target zone, and for time.

Our vehicle, the ORCA-1 , is designed to reliably, repeatably, and efficiently complete the course at a brisk speed under a wide variety of interfering conditions, component failures, and irregularities in the course layout.

Every component of our vehicle that we did not make ourselves can be mail-ordered and delivered within a day, which allowed a short design cycle and a relatively low budget. In addition, we made the design as modular as possible, to facilitate the replacement of failed components, and to allow us to incorporate new systems easily.

We chose an extremely simple main hull---a piece of PVC pipe sealed at each end with test plugs. The main hull provides buoyancy for the vehicle and serves as a dry

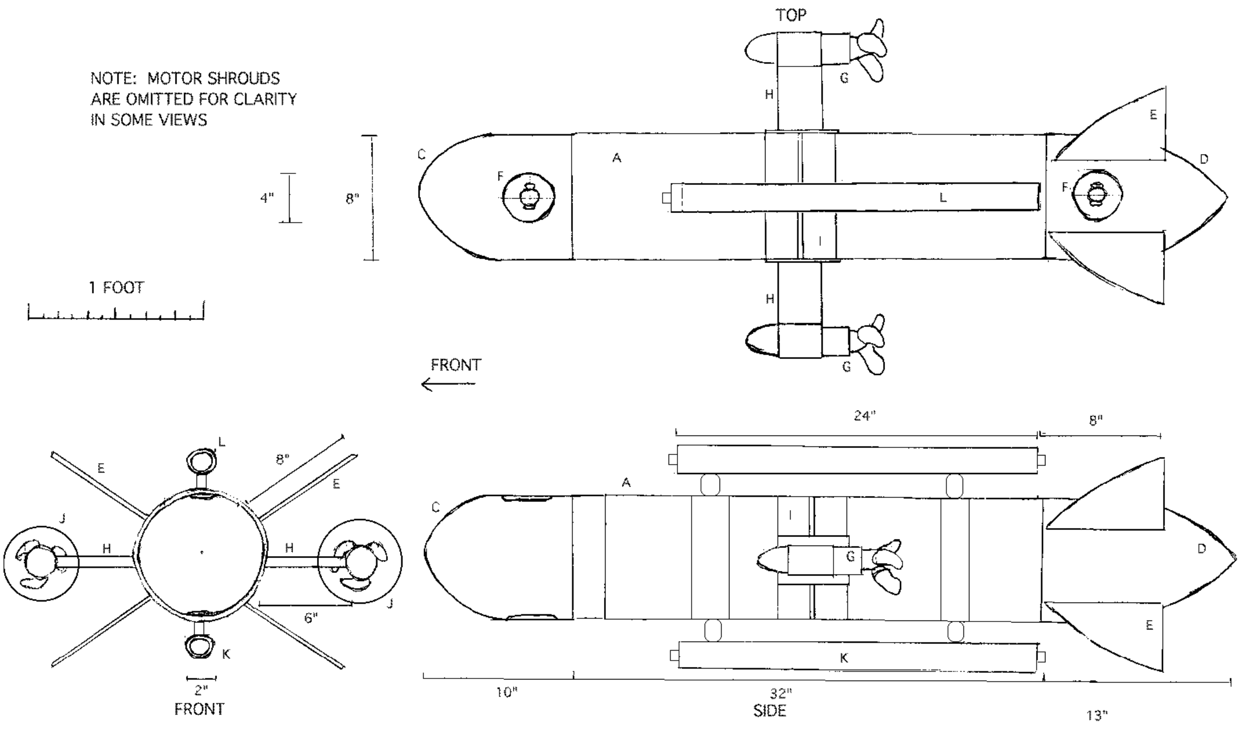

Figure 1: ORCA-1 Plan View.

compartment for the batteries and electronics. The vehicle is positively buoyant by approximately 2%, and is held at depth by two thrusters mounted in vertical holes through either end of the hull. There are two main thrusters, one on each side of the vehicle, allowing the vehicle to make differential turns in place. There are no movable control surfaces.

For navigation, we assembled an inertial navigation system from accelerometers and rate gyroscopes designed for automotive use. Steady-state error buildup in the system is canceled by a large and redundant array of sensors, including a water pressure sensor, a magnetic compass, and fluidic inclinometer. The navigation system returns a position in absolute pond coordinates throughout the mission.

The ORCA-1 has a forward-looking and a bottom-looking array of sonar transducers. These are used to find gates, map the target zone, and to recognize landmarks to further cancel error buildup in the navigation system.

The vehicle is controlled by a 586-based single board computer running the Linux operating system. The control program is single-threaded for maximum reliability.

Mechanical and Electrical Systems

The main body of the ORCA-1 is a 32” piece of 8î diameter PVC drain pipe (See Figures 1&2, A). The pipe serves as the watertight electronics compartment, the buoyancy volume, and the framework for mounting the thrusters. We chose PVC pipe because of its availability, machinability, and excellent mechanical and hydrodynamic properties. The hull is sealed at each end with commercial expanding test plugs rated to 30 PSI (B). The test plugs seal the hull quickly and reliably. The inside of the pipe is pressurized to 10 PSIG during operation to prevent water from leaking into the hull and to simplify leak detection. The vehicle is 48 kg and displaces 49 kg of water, making it positively buoyant by approximately 2%.

Bow and Stern Fairings and Vertical Thrusters

The cylindrical ORCA-1 chassis is streamlined by water-filled fairings on the bow (C) and stern (D). The bow fairing is rounded and shaped to accept a sonar transducer. It was hand-laid in fiberglass-epoxy using a Kitchen-Aid four quart mixing bowl as a mold. The stern fairing tapers to a conical point; it is constructed of a wireframe/fiberglass/polystyrene composite devised especially for this project. The stern fairing has four stabilizing fins mounted at 30 degrees from the horizontal mid-plane (E). Vertical thrusters mounted at the bow and stern provide thrust to dive, surface, and pitch (F). The vertical thrusters are shrouded by a 4” PVC duct mounted inside each fairing. The thrusters are built from motors removed from a Rule 1100 bilge pump, and 3” stainless steel propellers.

Main Thrusters

The ORCA-1 main thrusters are modified Sevylor electric outboard motors with customized 5” reversible propellers (G). We chose the motors for their low cost, power, and sealed design. Each motor draws 7A at 12V, and provides 17 pounds of thrust. The motors are mounted on fully-adjustable mounts, so that their position in the fore and aft (x axis) and vertical (y axis) planes can be adjusted for optimum performance. The motors attach to a TIG welded aluminum foil (H), which is attached to the hull with a clamping band made from PVC pipe and straightened hose clamps (I). The motors can be positioned independently by loosening the hose clamps and sliding the PVC rings as desired. A 6” diameter shroud made of PVC pipe is positioned over the main thrusters, to protect the propellers and their surroundings from being damaged (J). Also, the ends of the shrouds are covered with wire cages to keep unwanted material away from the propellers.

Motor Control

All four of the thrusters can be run at 32 discrete speeds in both directions. We use four Novak “Super Rooster” FET H-bridge PWM speed controllers, designed for radio-controlled cars, to drive the motors. Despite their low cost ($100), these units outperformed many OEM motor drivers that we evaluated. The units can switch 320 A at 12V, have an on resistance of less than 0.002 ohms, present a simple and reliable control interface, and have short circuit protection and thermal shutdown. A PIC microcontroller takes commands from the computer over an asynchronous serial port and generates TTL level PWM servo control signals for the speed controllers.

Pressurization and Through-Hull Connections

Fluid and electrical connections through the hull are made with Swagelok brass tube fittings, sealed with Teflon tape. A small-valved fitting is mounted on the hull to allow it to be pressurized with an air compressor. All through-hull electrical wires are internally sealed with epoxy to prevent water from leaking into the vehicle in the space between the conductors and the jacket.

Top and Bottom Fairings

To allow the mass and trim of the vehicle to be adjusted, a 28” section of 2” diameter flooded PVC pipe (K) is attached to the underside of the submarine. Brass disks slide into the tube and can be rigidly bolted in place. Disks can easily be added, removed and repositioned to adjust the buoyancy and trim of the submarine, without fine-tuning the position of any components inside the sealed hull.

A transparent air-filled tube of the same dimensions (L) is mounted on the top of the vehicle to center the drag on the vehicle and to provide additional buoyancy and stability in pitch and roll. A strobe light inside the front of the tube allows visual observation of the vehicle in murky water, and a vacuum florescent display mounted in the tube allows the software state of the vehicle to be determined at a glance.

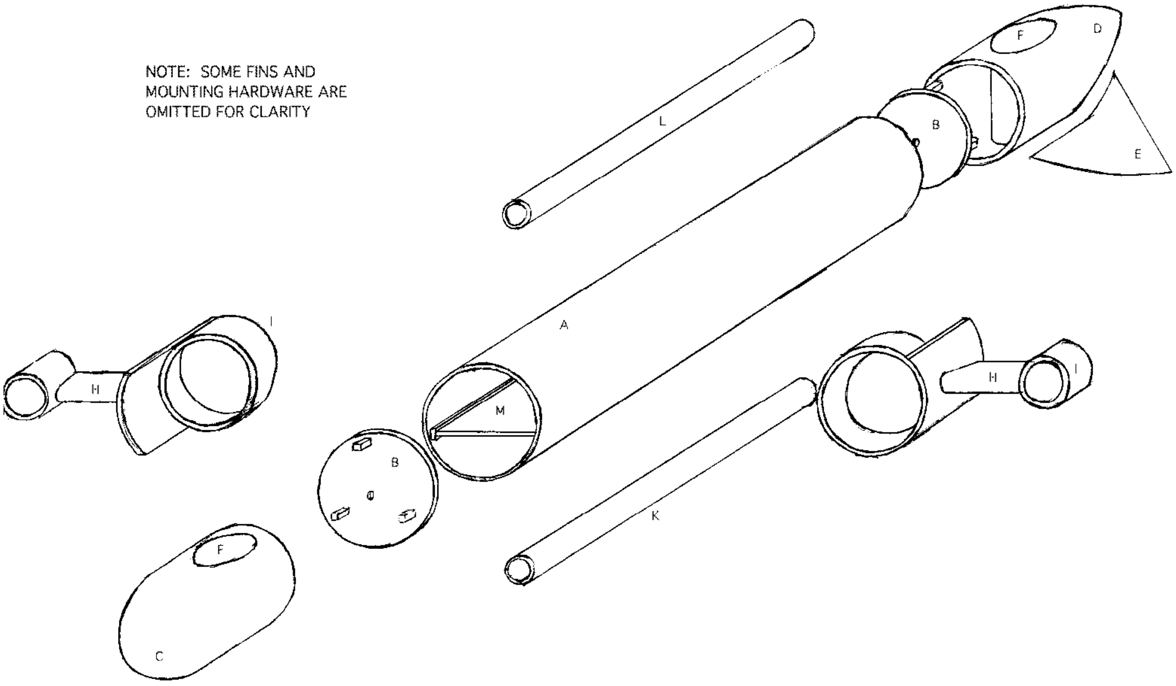

Figure 2: Exploded View of the ORCA-1

Target Zone Marker

The competition-supplied target zone marker deployment system bolts onto the stern side of the bottom trimming tube. A primary battery and a solid-state relay are used to provide the 24V, 2.5A, 3 second pulse needed to drop the marker.

Electronics Card

The electronics are mounted on a 6” wide, 28” acrylic plastic sheet (M) that slides on rails mounted at the lower 6” chord of the main hull. The electronics are mounted on top of the plate in aluminum boxes, and the batteries are mounted on the bottom. This design allows easy removal of the electronics for repair, testing, and replacement of the batteries. Concentrating the battery weight at the bottom of the hull provides natural roll stability.

Cooling System

The motor drivers, inertial measurement unit, and computer generate a significant amount of heat and require a dependable cooling system. The ORCA-1 uses a forced water active cooling system. A pump draws water from the pond and pumps it through brass heat sinks mounted on top of each of the main heat-producing components on the card. The used water is then ejected back into the pond.

Power Supply

The vehicle uses a bank of three 7.2 AH 12V sealed lead-acid gel-cell batteries to power the motors, and a fourth to power the electronics. For safety, a 50A main fuse cuts power to the vehicle in case of catastrophic failure, and a 49 MHz radio control unit can also be used to cut power, if necessary. A Lambda PM3012T0512 switching converter provides a regulated 5V supply for the computer. Both battery voltages are connected to A/D converter inputs for monitoring.

Imaging

The competition presents several imaging tasks: Imaging the depth gradient under the vehicle to follow an isobath, imaging the target zone to find the lowest point, determining the location of the gate uprights, and avoiding underwater obstacles, including competition officials.

We decided to use sonar instead of optics for all of these imaging tasks for the following reasons: First, all of the tasks require images with range information—while sonar images inherently have range information, extracting range information from an optical image is a difficult computational task. In addition, sonar can perform in murky water and under unknown lighting conditions, and can detect targets of any color or surface texture. On the other hand, accurate computer interpretation of optical images typically requires precise knowledge of lighting conditions and target characteristics. In addition, a potted sonar transducer is far more rugged than a glass camera lens.

ORCA-1 uses one bottom-looking sonar array to image the course and the target zone, and one forward-looking sonar array to

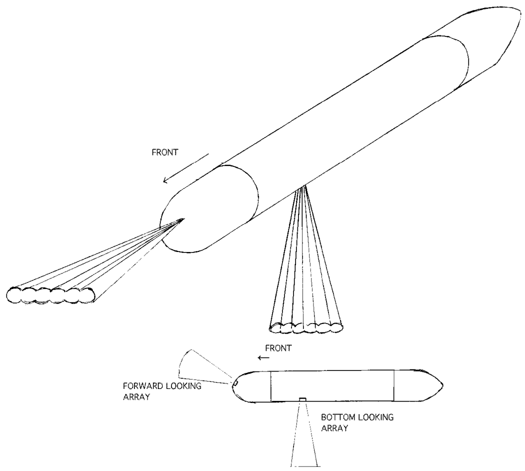

Figure 3: Sonar Beam Pattern

image uprights and obstacles (see above). We use two modified ìHumminbird Wide Paramount 3Dî fish finders, made by Techsonic Industries, as our sonar front-ends. Despite their low cost ($350 retail), they are surprisingly accurate units. They actively ping over a 53 degree plane angle using six conical 16 degree 455 kHz directional sonar beams. After each ping, the units demodulate and sample the return signal to three inch resolution. The modified units buffer and transmit the return data to the computer through an asynchronous serial port at a rate of five images per second. The computer normalizes each sonar return signal to compensate for water attenuation, and low-pass filters successive images over time to reduce the effects of uncorrelated acoustic noise.

To process the bottom-looking returns, the computer identifies the first large peak and records this as the bottom depth. To process the forward-looking returns, the computer convolves the reflection signature of a 4î PVC pipe with each return to make a plot of upright probability versus distance for each transducer. The computer makes a list of each large return, recording its transducer, range, and the probability that it is an upright. The computer then plots the possible uprights in Cartesian coordinates and, iterating over each, searches for upright patterns the size and shape of a gate or target zone. The computer uses simple thresholding to identify up to one target zone and up to three gates. Objects that are not determined to be uprights are marked as obstacles. The computer then generates a list of the heading, range, orientation, and probability of existence for each identified gate, target zone, and obstacle, and passes this list to the mission planning code.

Navigation

A) Logic

The ORCA-1 has a comprehensive and redundant array of navigational sensors that, coupled with sonar imaging, allow it to determine its speed, heading, attitude, and position at all times.

We use a water pressure sensor to measure depth, a magnetic compass to measure heading, a fluid-filled inclinometer to measure attitude, a magnetic impeller to measure speed, and a thermistor to measure water temperature. To complement these sensors, we use a six degree-of-freedom strap-down inertial measurement unit that measures the vehicle’s acceleration and rate of turn on each axis.

We implement an inertial navigation system by using an extended Kalman filter to process the data from all of the sensors into a least-squares maximum-likelihood estimate of the vehicle's position and orientation. The Kalman filter is written to time-integrate the rate of turn on each axis to determine the vehicle's orientation, rotate the measured acceleration vector by that orientation, and double-time-integrate the acceleration vector to calculate the vehicleís position in the inertial reference frame. This procedure accumulates a large amount of steady-state error, so the navigation code uses the following logic to select additional input data for the Kalman filter whenever possible.

1) Pitch, Roll, and Speed Correction

When the vehicle is not accelerating, that is, when the measured acceleration vector has a magnitude of 1 g, and a turn or speed change is not underway, we use the direction of the acceleration vector and the inclinometer reading to determine the vehicleís attitude, and feed this value into the Kalman filter. When the vehicle has not been accelerating for a long time, the impeller speed becomes accurate, so we input this value into the Kalman filter as well.

2) Heading Correction

Our compass module returns a three dimensional magnetic field vector. We rotate this vector by the attitude and take the component of the resultant that is parallel to the Earth's surface. The direction of this vector is our measured heading. The compass has a magnetic distortion alarm that compares the magnitude of the local magnetic field to a reference value. If the compass does not report magnetic distortion, we feed this heading into the Kalman filter.

3) Depth Correction

The pressure sensor reading is directly proportional to the vehicle’s depth. This value is scaled and input to the Kalman filter to fix our position absolutely on the Z axis.

4) Navigation Around The Perimeter

We model the pond as a section of an oblate spheroid, and use sensor data to correct our position in cylindrical coordinates. We use the slope of the pool stated in the contest description to map the measured depth to a radius r. If the vehicle has been going forward at a constant heading for a threshold time, and the depth of the water has not changed, we estimate that the vehicle is moving tangentially to the shoreline of the pond. In this case, the heading can be used to compute its position in θ around the pool. Each time a position in cylindrical coordinates is obtained, it is converted to Cartesian coordinates and input to the Kalman filter.

It should be noted that the level center region of the pool is a dead zone with this navigation system. If the vehicle should find itself in the center of the pool, it takes a constant heading toward the last-known-closest perimeter.

5) Target Zone Navigation

The procedure for mapping the target zone (detailed below) is designed to make the vehicle cross over the edges of the raised platform of the target zone as often as possible. Every time the bottom-scanning sonar shows a sharp rise from or a sharp drop to the approximately 3 m depth of the pond around the target zone, the vehicle's position on one linear axis relative to the target zone is known and is fed into the Kalman filter.

B) Sensors

1) Inertial Measurement Unit

The inertial sensor package consists of two inexpensive ($150) Gyration MG100 two-axis piezoelectric tuning fork rate gyroscopes, and three inexpensive ($20) Analog Devices ADXL50 silicon micromachined accelerometers. These rate gyros have a resolution of 0.1 degrees/sec, a full-scale range of 150 degrees/sec, and a bandwidth of 10 Hz. The accelerometers have a resolution of 5 milli-g, a full scale range of 5 g, and a bandwidth of 6 kHz. Both of these sensors provide analog outputs for which we have designed a custom acquisition and filtering system.

Each sensorís output is appropriately filtered and amplified by laser-trimmed instrumentation amplifiers. These signals are scaled to the proper 0-5V range for the A/D converter. A set of multiplexers selects which of the 10 derived voltages is to be converted. This voltage is then sampled and digitized by a 100Ksps 16-bit A/D converter.

A PIC16C76 microcontroller manages the A/D converter and the multiplexers. It keeps a running 10-pole FIR filter on each value, and queues the values for output on demand to the main computer. The navigation unit is connected to the main computer using the EPP parallel port. A secondary output provides for near-real time monitoring via a high speed serial port.

EMI, RFI, temperature, and humidity cause a large amount of offset drift, so the inertial sensor package is potted into a grounded cast aluminum box which is sealed, thermally insulated, and cooled to 45ºF by a Peltier effect thermoelectric heat pump. A PI controller manages the box temperature and pumps heat from the sensors into the vehicle's water cooling system.

2) Depth Sensor

We use an Omega Engineering PX202-015AV thin film pressure sensor to measure our depth. It has a full scale range of 30 PSIA, and an error due to the combined effects of linearity and hysteresis of less than 0.25% with temperature compensation, which allows us to measure depth to a resolution of 2 cm.

The pressure sensor is mounted on the electronics card. It connects to the outside environment with flexible plastic hose. Its electrical output connects to one of the A/D inputs on the I/O card.

3) Compass Module

The ORCA-1 is equipped with a TCM2-20 magnetic compass module from Precision Navigation. It has a magneto-inductive three axis magnetometer, a fluid-filled inclinometer, and a microprocessor that filters out hard iron distortion and alerts the computer to soft iron distortion.

4) Velocimeters

The vehicle has two magnetic impeller velocimeters, one mounted on top of each motor mount. The rotation rate of each of these impellers is measured by a hall effect sensor. The electrical outputs of the sensors connects to a counter on the I/O board.

C) Kalman Filter Implementation

The state vector contains values that are stored in global coordinates; all sensor readings are immediately translated into global coordinates for simplicity and then filtered. An extended Kalman filter (EKF) processes input from the inertial measurement unit and other sensors, as described above. A feedback loop takes the output of the EKF and uses it to adjust parameters (gyro bias, accelerometer misalignment) used by the inertial guidance system to calculate its trajectory. Simultaneously, a feedforward configuration calculates the expected error in the final trajectory values, and the feedback and feedforward EKF values are then compared to see whether the EKF is in a divergent state. If it is, the filters are reset and the process restarted. We expect to run the inertial navigation system at rates approaching 50 Hz, with corrections from the absolute sensors every few seconds, and hard sonar and mapping corrections every few minutes.

Mission Strategy

When the ORCA-1 is released from the dock, it orients itself to face to the right, dives to 2 m, and travels along a pre-programmed course toward the shore on the right-hand side of the dock. When it reaches the three meter isobath, it proceeds around it in the counterclockwise direction.

When the vehicle detects a gate while following the isobath, and the gate is not farther from the isobath than a pre-determined threshold, it steers toward the gate, goes through it, and returns to the isobath.

After the vehicle goes through the sixth gate, and a target zone is detected with greater than a threshold probability, or after it has gone through fewer than six gates, and a target zone is detected with high probability, it turns left into the target zone and makes a map of it. To map the target zone, the vehicle executes a pre-programmed traversal sequence. The vehicle makes three evenly spaced passes over the target zone in X, and three evenly spaced passes in Y, interleaving the X and Y passes to allow the navigation system to get a hard sonar correction on each axis (by detecting the sharp edge of the target zone’s raised platform) as often as possible. Three passes are needed so that our six discrete-beam sonar can resolve target zone features to a resolution of 20 cm.

Once the vehicle has scanned the target zone, it calculates the location of the lowest point and returns to it. If the measured water depth at that point is correct, it drops the marker beacon. Otherwise, it searches for the correct depth in a spiral pattern.

After it has dropped the beacon, it moves to the center of the target zone, spins in a circle to verify its position relative to the target zone uprights, and surfaces.

At any time, if the vehicle detects an obstacle in its path, it turns to avoid it. If the vehicle is running its motors but not moving, it executes “evasive maneuvers,” backing up, turning, and going forward repeatedly, in an attempt to free itself.

Control Computer

The ORCA-1 is controlled by a WinSystems LBC-586-C single board computer that has an AMD 586 CPU and 32 MB of RAM. The board has four serial ports, a Centronics parallel port, 48 digital I/O lines, a NE2000 compatible Ethernet Interface, and a PC/104 stack connector. The computer uses a 20 MB IDE solid-state flash disk for program storage. When the vehicle is tethered, we use TCP/IP over Ethernet to control the vehicle, read telemetry, and modify or debug the control program.

The computer runs the Debian/GNU Linux 2.0.34 operating system. We chose Linux because of its stability, familiarity, and open architecture. The control program is written in C and is single threaded for maximum reliability.

A 2 line by 40 character vacuum fluorescent display in the transparent top fairing displays console messages, diagnostic information, and the current mission status.

Physical Modeling and Simulation

We wrote a submarine simulator so that we could test and debug our algorithms as much as possible on dry land. We used a linear-time dynamics system which uses the 6-dimensional Featherstone recursive algorithm to quickly simulate the relevant physics in near-real time on a standard PC. The modeling system allows one to easily add collision geometries, force fields, friction, and other useful mechanical primitives to the environment.[2]

Software Organization

The software is organized as an asynchronous control loop. The loop has six tasks: Imaging, Navigation, Planning, Steering, and Display.

The Imaging code gets the most recent echo return from the sonar and runs the imaging algorithm described above. It returns the bottom depth under each transducer and a list of gate, target zone, and obstacle positions.

The Navigation code gets the most recent reading from all of the sensors and implements the navigation scheme described above. It takes a flag indicating whether the vehicle is in the target zone, and returns the vehicle’s current position in global pond coordinates, its heading and attitude, and its velocity.

The Planning code takes data from the imaging and navigation code, analyzes it, and returns a new desired heading and depth based on the mission strategy described above. It is implemented as a state machine with a number of internal state variables, such as the number of gates traversed, the elapsed time, whether the vehicle is traversing the perimeter or in the target zone, the lowest target zone depth, and so on.

The Steering code takes the desired heading and depth, along with the vehicle’s current heading, depth, velocity, and attitude, and PID controls the horizontal and vertical thrusters to approach that heading.

The Display portion of the code displays all of the variables named above to the user console, which is accessible by the Ethernet tether, so that the user can observe them during program debugging. It also allows the user to remotely control the vehicle, if necessary.

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[2] A description of our dynamics simulator can be found at *http://web.mit.edu/eboyden3/www/dynamics.pdf.*

Conclusion

In designing this vehicle, we were inspired by the post-cold-war spirit of efficient, cost-effective engineering exemplified by the Mars Pathfinder.

We built this vehicle on a short design cycle using readily available components and modified consumer products. In addition to lending a great deal of pre-tested reliability to the system, this approach allowed us to build a modular vehicle that could be easily modified as testing determined that new or different systems were required.

Rather than building an expensive, feature-laden vehicle that could be used to accomplish a wide variety of missions, we built a cost-effective, simple vehicle targeted specifically at this mission.

Our motor drivers provide a good example of this approach. We priced OEM motor driver blocks, but units that could handle motors of this power were very expensive. We considered building our own motor driver modules, but then found that an inexpensive, reliable, high-performance, readily-available solution already existed---the Novak “Super Rooster,” a $100 speed control unit for radio controlled cars. We took one apart, confirmed that its characteristics met our specifications, and verified that it was soundly constructed. The manufacturer’s technical staff verified its suitability for our application, and finally, we subjected the device to a battery of tests, culminating in an in-situ performance test.

Another major design goal was reliability. The ORCA-1 has a redundant array of electronic and mechanical sensors that generate a robust picture of the vehicle’s navigational state. Should there be multiple sensor failures, the vehicle should still be able to navigate the course, but with a lower tolerance to variation of course features and environmental disturbances.

With our modular design and redundant sensor array we believe that we have a design for a vehicle that can accomplish the mission “Better, Cheaper, Faster.”

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