

# ORCA-2: Old Dog, New Tricks



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## **Abstract**

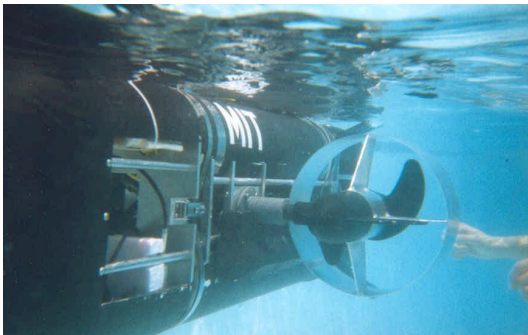
The ORCA-2 is a fully autonomous submarine originally built for the Second Annual International Autonomous Underwater Vehicle competition. The vehicle is 60" long, 32" wide, and has a mass of 50 kg. Side-mounted thrusters are used to drive and differentially turn, and vertically mounted thrusters are used to dive, pitch, and hold the vehicle at depth. The vehicle is powered by a 420 watt-hour sealed lead-acid gel-cell battery, has a top speed of 1.8 m/s, and operates for 2 hours on a single charge. It also has a suite of navigational sensors including a magnetic compass, water pressure depth sensor, solid-state inclinometer, and 6-degree of freedom inertial measurement unit. ORCA-2's modular construction facilitates the addition and removal of components without compromising the integrity of major systems like the watertight hull, electrical power rails or the central computer. An onboard Pentium-based computer running Linux provides a robust centralized control platform. For development, the vehicle can be monitored from on-shore computers, using a spread-spectrum radio data link.

To meet the new requirements posed by the 2000 competition ORCA-2 has been refitted with new equipment. The upgraded ORCA-2 uses an array of four hydrophones to triangulate the position of the sonar beacon on the target. The vehicle tracks its absolute position in the pond with a 300 kHz Doppler velocity log system. When the vehicle is close to the target, it uses a video camera to visually locate the orange ring and use a retracting hook to capture the ring.

## Introduction

The ORCA II is designed to complete the challenges and comply with all the rules specified by The International Autonomous Underwater Vehicle Competition. A summary of the contest rules is as follows. The contest arena is Lago Dorado, on the grounds of the Coronado Springs Resort at Walt Disney World, in Orlando, Florida. The arena is roughly oval in shape, 150 m by 90 m, and has a maximum depth of 3 m at the center. Several beacon stations, consisting of an orange ring one foot in diameter, a sonar transmitter, and a strobe light, are hidden throughout the pond. At the start of each run one of the stations will be turned on causing the light to flash once every one to three seconds, and the sonar to ping once every 20-30 seconds. Each team's fully autonomous submarine must find the orange ring and bring it to the surface. The vehicle is not permitted to drop navigation beacons or utilize a Global Positioning System. Points are awarded for controlled motion, determining the flash rate of the strobe, determining the ping rate of the sonar transmitter, recovering the ring, and time.

Our vehicle, the ORCA-2, is designed to



**Photo 1: ORCA-2 From Underwater**

recover the ring reliably, repeat ably, and efficiently, under a wide variety of interfering conditions. The design was made as modular as possible, to facilitate the replacement of failed components and the introduction new systems.

## Design Overview

The hull of the ORCA-2 is designed to be a modular, flexible, easy-to-use platform for an electronic payload. The main hull has two dry compartments that house the batteries and electronic systems. It also has two open compartments that flood with water where sonar transducers, a video camera, and gripper hardware are mounted. The vehicle is positively buoyant by approximately 2%, and is held at depth by two thrusters mounted in vertical ducts in streamlined modules mounted at the bow and stern of the hull. The two main thrusters are mounted on either side of the vehicle, allowing differential turns.

The vehicle is controlled by an onboard computer running the Linux operating system. A spread-spectrum radio data link allows the submarine to be controlled from on-shore laptop computers for testing purposes. The operators can observe all sensor readings and internal state with a



**Photo 2: ORCA-2 From Above**

graphical user interface. The control program can also be run in simulator mode, using a mathematical model of the pond to generate simulated noisy sensor data, so that control code can be debugged on land before it is tested in the water.

The ORCA-2 has a Doppler Velocity Log navigation system, which calculates the vehicle's position in the pond by integrating the measured bottom velocity. The vehicle is also equipped with an array of four hydrophones, which it uses to find bearings to the sonar beacon at several locations around the pond. It uses the bearings to triangulate the location of the beacon, then maneuvers to that location, and uses a video camera to search for the orange ring in a spiral pattern. Once it finds the ring, it pauses to measure the flash rate, then captures the ring and returns to the surface.

## Mechanical and Electrical Systems

The hull of the ORCA-2 has twin dry compartments that contain the electronic systems. The compartments are made of six-inch diameter PVC pipe, and are 27 inches long. The tubes are mounted on an aluminum frame (Figure 2), one above the other. A gasketed PVC plate is bolted to the stern end of each pipe. All through-hull electrical connections are made with bulkhead connectors mounted in these plates. The bow end of each pipe is sealed using commercially available test plugs, providing easy access to the dry compartments. The top compartment holds the computer, compass, inertial sensors, radio transceiver, and antenna. The bottom compartment contains the batteries and power electronics. This arrangement was

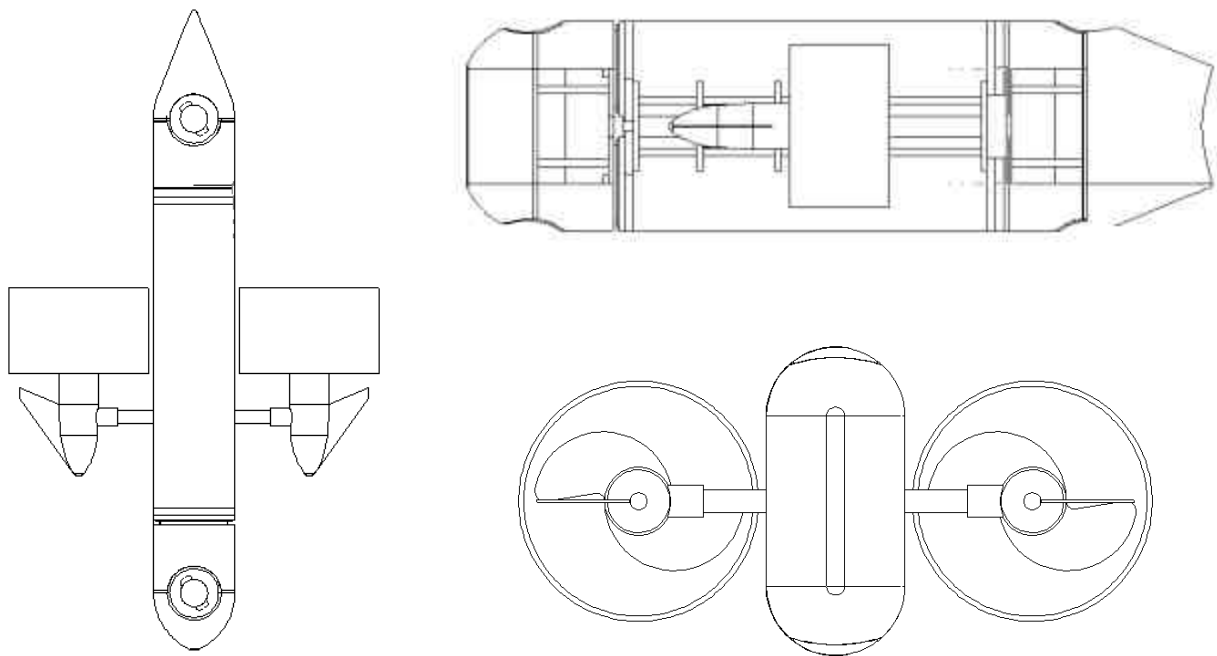


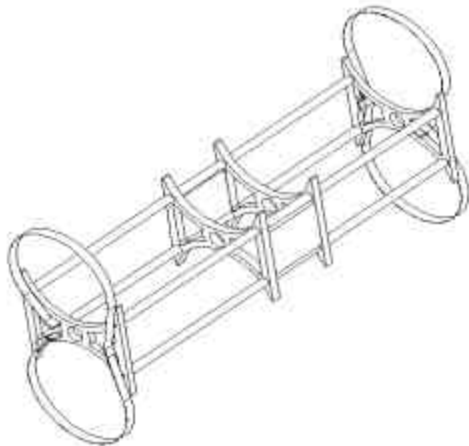
Figure 1: Mechanical Drawings

chosen to make the location of the batteries, the heaviest part of the vehicle, as low as possible, to lower the metacentric height and increase the righting moment of the vehicle. Tests have confirmed that the ORCA-2 is very stable in pitch and roll. Streamlined flooded modules (Figure 3) are mounted at the bow and stern of the vehicle. These modules attach to the aluminum frame with hinges and swing aside to allow access to the electronics compartments and connector panels. Each module contains a vertical thruster duct and a flooded compartment. The flooded compartments hold the Doppler velocity logger navigation system, the video camera, a floodlight, a sonar rangefinder, the hydrophones, the ring recovery hook, and the competition supplied tracking beacon. Each dry electronics compartment holds a slide-out aluminum card, on which all of the electronics are mounted. The card connects to the compartment's aluminum end plate with a blind-mating multi-pin connector, so that it can be removed without disconnecting any cables. The ORCA-1 had to be partially disassembled to access the internal

electronics, a process that involved the removal of several screws and over ten connectors. The ORCA-2 can be opened in less than 15 seconds with a single wrench (to open the commercial test plug), and the electronics can be removed, and serviced without disconnecting any cables.

### **Bow and Stern Hull Modules**

The bow and stern hull modules (Figure 3) consist of an aluminum frame, a vertical thruster duct, and a streamlined fairing. The fairings are made from ABS plastic and are shaped to give the vehicle a roughly teardrop shape that increases its hydrodynamic performance and power efficiency. The aluminum frame of each hull module provides a structure to securely attach the outboard equipment.



**Figure 2: Aluminum Chassis**



**Figure 3: Forward Hull Module**

## **Vertical Thrusters**

The vertical thrusters are shrouded by 4-inch ducts mounted in the bow and stern hull modules. The thrusters are made from sealed motors removed from Rule 1100 bilge pumps and 2.75 inch RC boat propellers. Each thruster is streamlined with fairings made from PVC, to improve the flow of water through the duct and decrease power loss.

## **Main Thrusters**

The main thrusters are Minn-Kota reversible electric outboard motors with 10" propellers. We chose these motors for their high power, reasonable cost, rugged design, and double O-ring seal. Each motor draws 15A at 12V, and generates 30 pounds of thrust. The motors are mounted to the aluminum frame on an adjustable carriage so that they can be positioned to maximize performance. An 11-inch aluminum shroud is clamped around each thruster for safety.

## **Motor Control**

All four of the thrusters can be run at 32 discrete speeds in both directions. To drive the motors, we use four Novak "Super Rooster" FET H-bridge PWM speed controllers, designed for radio-controlled cars. Despite their low cost (\$100), these units outperformed many OEM motor drivers that we evaluated. The units can switch over 40A at 12V, have an on-resistance of less than .002 ohms, present a simple and reliable control interface, and have short-circuit protection and thermal shutdown. An SH1 embedded controller takes commands from the computer over an

RS-232 port, and generates the servo signals needed to operate the speed controllers. The servo signals connect to the motor drivers through 74OL6010 optoisolators to prevent the coupling of electrical noise from the motors.

## **Electrical Connections**

Electrical connections through the hull are made with hermetically sealed locking multi-pin connectors made by W. W. Fisher. The connectors cost about \$30 each, and are rated to 250 feet of water. Each outboard component connects to the vehicle using its own connector mounted in the PVC plugs at the stern end of each electronics compartment. In addition to the outboard component connectors, there is a jumper cable connecting the two electronics compartments and a tether connector for development and testing.

## **Recovery Hook**

The vehicle needs a reliable means of capturing and holding the ring during recovery. The ORCA-2 is equipped with an eight inch articulated hook made of PVC. The hook is mounted in the bow compartment frame and normally sits retracted in the compartment. The hook is extended below the vehicle with a hydraulic piston just before it moves to recover the ring. A Rule 800 sealed bilge pump supplies the pressure needed to actuate the piston. A video camera mounted behind the hook is used to guide it through the center of the bright orange ring. Once the ring is entrapped, the pump motor is deactivated and the spring-loaded piston retracts into the vehicle. With the hook is retracted, the ring is totally enclosed by the hook and is held

against the vehicle with five pounds of force. This allows the vehicle to maneuver in any direction without dropping the ring.

The mounting structure for the hook is equipped with optical sensors that indicate its position. This allows ORCA-2 to sense if it has the ring so it can make another attempt if it does not.

### **Electronics Cards**

All electronics are mounted on slide-out aluminum cards for bench-top servicing. The power electronics, fuse box, are mounted on one six inch wide, 24 inch long reinforced aluminum sheet. The batteries are mounted on an identical aluminum sheet that bolts to its underside, forming a single card. This card slides into PVC rails attached to the insides of the bottom electronics compartment. This arrangement allows the batteries to be easily replaced, to extend testing time. All electrical connections from the card to the compartment's stern connection plate are made through a mating pair of ELCON "75A Middle Drawer" backplane connectors, which mate automatically when the card is pushed into the compartment. In the top compartment, the computer and sensing electronics are mounted on a similar card. The top card has a hole pattern drilled into it, to facilitate addition and rearrangement of components. Electrical connections from the top card are made with a mating pair of ELCON "Lower Drawer" backplane connectors.

### **Power Supply**

The vehicle uses a bank of three 7.2 AH 12V sealed lead-acid gel-cell batteries to power the thrusters, and a fourth to power

the electronics. A Lambda PM3012to512 switching converter provides 5V at 5A for the computer, and +/-12V at 1A for analog circuitry. Each battery bank, power supply voltage, and motor has its own fuse in an ATO/ATC automotive fuse box. Power from the batteries is switched through a set of Siemens VF4-81F11 40A mechanical relays. Two waterproof mechanical switches with colored rip cords can be used to power down the motors or the entire vehicle.

### **Monitoring System**

The temperature and pressure in each electronics compartment are measured using an LM35 temperature sensor and an ASCX30AN 30PSIA pressure transducer. The motor and electronics battery currents are measured using two LEM LV25-P Hall Effect Current Sensors. The motor and electronics battery voltages are measured using two LA55-P galvanically isolated voltage sensors. Sensors mounted in the lower compartment connect to A/D inputs on the motor controller microprocessor. Sensors mounted in the top electronics compartment connect to A/D inputs on the PC/104 stack. These sensors allow us to detect electrical failures, low-battery conditions, and leaks before they render the vehicle inoperable.

### **Imaging**

The ORCA-2 is equipped with a machine-vision system composed of an Aurora color video camera made by Insite Tritech and a PC/104 based frame grabber board from Ajeco. The vehicle collects digital images of the region in front of it and processes them in real-time to positively identify the location and orientation of the target ring. There is

also an array of 4 flood lamps mounted on the bow of the vehicle to ensure adequate brightness for the image processing.

The images are first pre-processed to normalize the brightness and contrast. Then the outline of the ring is identified using a median filter algorithm. The distance between each orange pixel and the center of the field of view is averaged to give the position of the center of the ring relative to the center of the field. The algorithm then sends the horizontal and vertical distances needed to center the ring in the field to the main navigational program. The algorithm also encloses the orange region in a box and uses the aspect ratio of this box to determine the angular orientation of the ring.

### **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) 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 sensor's output is appropriately filtered and amplified by laser-trimmed instrumentation amplifiers and the signals are scaled to the proper 0-5V range for the A/D converter. A set of multiplexers selects which of the 10 desired 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 IMU is connected to the main computer using an RS-232 serial port.

### **Compass Module**

The ORCA-2 is equipped with a HMR3000 compass from Honeywell. It has a magneto-resistive three-axis magnetometer and a solid-state inclination sensor. The unit is mounted on the internal electronics card with special consideration to keep it away from the strong magnetic fields generated by the motors and hard drive.

### **Altimeter**

The ORCA-2 uses a PA500 sonar altimeter to measure its height from the floor of the pond. This unit was selected for its accurate and rugged performance that was proved onboard our vehicles in the past two competitions. The sonar transmits at 500 kHz focused in a 6° conical beam and returns the altitude over an RS-232 serial interface. The unit is accurate in the range from 10 cm to 10 m, which is suitable for the depth of the competition arena.

### **Depth Sensor**

To measure depth, we use a Sensotec TJE series pressure sensor. It has a full-scale range of 50 PSIA, and temperature-compensated accuracy of +/-0.12%, producing a depth measurement accurate to +/- 1.3 cm. The voltage output of the pressure sensor is connected to a Diamond Systems MM-16 A/D converter card in the PC/104 stack. The pressure sensor used on the ORCA-1 had a millivolt level output,

which made it very susceptible to radio-frequency interference from the 1 W radio transmitter, and often caused erroneous depth readings. The pressure sensor used on the ORCA-2 has a 0-5V output, which is over 1000 times less susceptible to this type of interference.

### **Doppler Vehicle Log (DVL)**

Our sub is equipped with a 300 kHz Workhorse Navigator Doppler Vehicle Logger from RD Instruments. This system provides real-time position and velocity information in up north coordinates via an RS232 link. With a typical accumulated error of 0.4% of the distance travel, the DVL provides a confident measure of absolute position. We leverage that accuracy to combine data collected at multiple points along our trajectory to build a more complete worldview.

### **Hydrophone Array**

The ORCA-2 uses an array of vehicle-mounted hydrophones to locate the sonar beacon. Four hydrophones are mounted on the vehicle, one each on the bow and stern, and one each on the port and starboard, next to the motor mounts. The vehicle uses a custom-built data acquisition and signal processing system to measure the difference in arrival time of each ping at each of the hydrophones, and uses this to find a bearing to the beacon.

In order to facilitate rapid development and testing, we decided to do as much of the processing as possible in the submarine's main computer, since this would allow us to use the rapid development and testing environment used for mission planning code

for the sonar signal processing code as well. At the same time, we wanted to avoid running analog signals directly to a PC/104 A/D card, since the electrical environment inside the submarine is very harsh.

Each hydrophone is mounted onto a small piece of PVC pipe that contains an amplifier, analog-to-digital converter, and DSP microprocessor. These hydrophone modules are daisy-chained together to the main system processor with an RS-485 bus.

The DSP microcontroller programmed to acquire and trigger the hydrophone signal in a manner similar to a digital storage oscilloscope: It continuously samples and stores the signal into a circular buffer. When it is triggered by 27 kHz energy in the signal, it acquires a set number of additional samples, then stops sampling. The main computer can then read out the entire circular buffer, which contains a snapshot of the signal before, during, and after the trigger event. The DSP triggers when the derivative of the magnitude of 27 kHz signal energy passes above a pre-set threshold. All of the data acquisition parameters (pre-trigger samples, post-trigger samples, carrier frequency, and derivative threshold) can be set remotely by the main computer. The hydrophone module marks each acquired signal with a timestamp, so that the main computer can compare it to signals from other hydrophone modules.

When a ping occurs, the main computer downloads the snapshot of it taken by each hydrophone, and uses the timestamps to plot all of the signals on the same time axis. The computer non-causally finds the advent of 27 kHz energy in each signal, and computes all of the pair-wise delay times of the advent



of first energy from hydrophone to hydrophone. Then, it computes the pair-wise cross-correlation functions of the signals, over a limited range. The range of the cross-correlation lags used for the computation for each pair is plus and minus one-quarter carrier cycle around the previously estimated advent of energy for that pair. The system then finds the peak in each pair-wise cross-correlation function over the calculated range; the cross-correlation lag at this peak is the precise pair-wise signal delay.

The angle between the endfire axis of the hydrophone pair and the sonar transmitter is given by

$$\mathbf{q} = \cos^{-1}\left(\frac{cd}{s}\right)$$

where  $d$  is the computed pair-wise delay,  $c$  is the speed of sound in water (1500 m/s) and  $s$  is the spacing between the hydrophone pair. As inverse cosine is a non-linear function, the returned angle  $\theta$  is more or less accurate for certain values of the delay. In particular, if the transmitter is endfire to the hydrophone pair, the angle estimate is least accurate (because the slope of the inverse cosine function is near zero) and if the sonar beacon is broadside to the hydrophone array, the angle estimate is most accurate. The computer computes all 8 4x4 pair-wise angle estimates, and combines them with a Kalman filter to produce an accurate estimate of the bearing to the beacon.

## Control Computer

All navigation and control code is implemented on a Pentium-based PC/104 embedded computer, running the Linux

operating system. We chose this computing platform for its familiar and flexible programming environment, remote operability, and the availability of modular, standard peripherals.

## Development

For development and testing purposes, the computer uses a multicast UDP protocol to communicate with multiple on-shore computers. From each station, the vehicle can be remotely controlled with a stick, and all variables and sensor values can be inspected and modified with a graphical user interface. In addition, the main control program can be modified and re-compiled. All of this can be done while the submarine is submerged and operational. The control program has a simulation mode, which uses a simple mathematical model of the pond and the vehicle to generate simulated noisy sensor data in response to motor commands. The simulation mode allows control code to be developed and debugged in the lab before it is tested in the water.

## Tether and Data Link

The wireless data link is a pair of Freewave DGRO frequency-hopping spread spectrum data transceivers. These devices operate over the 902-928 MHz frequency band, transmitting at 1 W. They connect to the host computer using an RS-232 serial port, and have a maximum data rate of 115 kbps/sec. In air, they have a 20-mile line-of-sight range, but with one unit underwater, depth becomes the limiting factor. In a chlorinated swimming pool, the units perform well up to a depth of about 2 meters. Communication with the vehicle can also be established using an Ethernet tether.

## **Mission Strategy**

The ORCA-2 will use the highly accurate absolute positioning capability of the DVL to combine several measurements from the passive sonar array to triangulate the position of the beacon. Once a position of the beacon has been determined, the sub will navigate to a position 5m due {South} of the beacon. Since the broad side of the ring faces north south, coming from due south will present the maximum aspect of the ring to the vision system. ORCA-2 will proceed due North until the vision system acquires the ring, at which time control will be transferred from the DVL and passive sonar systems to the vision system. The vision system will use the aspect ratio of the ring's bounding box to keep the sub orthogonal to the ring and the center of mass to keep the sub centered on the ring. Once the vehicle is positioned to recover the ring it uses the retrieval hook will capture it and the vehicle will surface. During the entire grappling procedure if the sub should lose visual contact with the ring, the Doppler navigation system will take over and return the sub to the position and orientation where the ring was last visible.

## **Conclusion**

The ORCA-2's modular design has allowed us to outfit the vehicle for a new mission with minimal impact on the existing systems. This allowed the development time to be greatly shortened, and for most of the work to be focused on new systems. As of the writing of this paper, the hardware platform has been nearly completed, and much of the software has been written. We have tested

the vehicle under both joystick and autonomous control, and tested the sensors in the pool. Development is proceeding well, and we look forward to competing with the vehicle in Florida.

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