# ORCA-IV: An Autonomous Underwater Vehicle

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The ORCA-IV is a fully autonomous submarine that we are building to enter in the Fourth Annual International Autonomous Underwater Vehicle Competition. Most of the vehicle's systems, including the hull, propulsion and CPU, are reused from the ORCA-II, our competition entry in 1999 and 2000. The utility and reliability of these systems allow development work to focus on new sensors and mission strategy tailored to complete the competition objectives.

The ORCA-IV is 1.8 m long, 0.8 m wide, and has a mass of 50 kg. Side mounted thrusters propel the vehicle at up to 1.8 m/s, while 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 battery and operates for 2 hours on a single charge. The vehicle has a wide array of navigational sensors, including a water pressure depth sensor, an active sonar altimeter, a magnetic compass and a three-axis rate gyroscope. The ORCA-IV uses a Doppler velocity log system for three-axis closed-loop velocity control. To navigate to the beacon, the ORCA-IV uses two custom-designed directional sensors. An array of four omni-directional hydrophones is used to determine the bearing to the acoustic transmitter. An array of eight directional light sensors is used to determine the bearing to the light source. A Pentium-based PC/104 computer runs software to control the vehicle.

# Introduction

The ORCA-IV is designed to fulfill the requirements and restrictions of the Fourth International Autonomous Underwater Vehicle Competition, which will take place at the U.S. Naval Academy in Annapolis, Maryland. The competition arena is a creek that flows into a tidal river. Its salinity is 7 ppt and it is about 4 m deep at its center. Five beacons will be scattered in the arena. Each beacon has a sonar transmitter that sounds a ping once every 20-40 seconds and a strobe light that flashes once every 1-2 seconds. The beacons have removable recovery markers attached to them. A linear array of two-foot-square platforms is aligned with each beacon. Only one of the beacons will be active during the competition run. There is also a single underwater validation gate.

The mission is for the vehicle to pass through the validation gate, determine the ping rate of the acoustic transmitter, gauge which of the square platforms in line with the active beacon is shallowest, retrieve the recovery marker from the beacon and return to the launching station. Points are awarded for each of these tasks, for time, and for various subjective measures.

**Photo 1: ORCA-IV From Above**

The ORCA-IV is designed to complete this course reliably and reproducibly, under various adverse conditions. Introduced two years ago, the modular design of the ORCA-IV has provided a solid hardware and software platform enabling the integration and testing of new systems and strategies. The team has adopted a design philosophy for making modifications to the core systems of the ORCA-IV: to upgrade single parts or subsystems leaving the interface to the rest of the system unchanged. This allows changes to be made with a reduced risk of rendering the vehicle inoperable for long periods of time. By keeping the vehicle in an operational state, the team can maximize practice time on a test course.

The vehicle is designed to run completely autonomously, but is equipped with various human interfaces to facilitate development work. A tether can be attached to the vehicle that provides an Ethernet connection to the on-board computer and a composite video feed from a CCD camera externally mounted on the vehicle. A 900 MHz spread-spectrum radio data link provides a wireless interface to the vehicle's computer.

Safety is a primary design goal for the ORCA-IV. All propellers are shrouded and all batteries are fuse-protected. An "all-stop" command can be sent over the radio link, and a brightly colored external rip-cord directly disconnects the batteries.

# Design

## Overview

The hull of the ORCA-IV is designed to be a flexible modular platform for an electronic payload. The hull has two dry compartments that house the batteries and electronic systems. There are also two open flooded compartments at the fore and the aft of the vehicle to house sonar equipment, light sensors and gripper hardware. In addition, an underwater video camera and floodlight are mounted on the bow. The vehicle is positively buoyant by 2% and is held at depth with two ducted vertical thrusters placed in the bow and stern. Two primary thrusters, mounted on the sides of the vehicle, are used to propel the vehicle forward and turn differentially. The ORCA-IV has a top speed of 1.8 m/s.

An onboard computer running the Linux operating system controls the vehicle. With the aid of a spread-spectrum radio data link the submarine may be directly controlled from on-shore computers during test runs. Team members can view sensor data with a graphical user interface and can view a live video feed with a shore-side monitor. The control code can also be run in simulator mode. The simulator uses a model of the arena to provide simulated sensor data so that control code can be debugged before deploying the vehicle in the water.

The ORCA-IV controls its depth with feedback from a water pressure sensor. It controls its attitude using a three-axis rate gyroscope and a magnetic compass. To navigate toward the beacon, the vehicle uses directional information from a hydrophone array and a directional light sensor. The vehicle is with a device to capture and hold the recovery marker. A sonar altimeter is used to measure the height of the shallowest object.

One concern in designing a strategy for the competition is that the arena is in a creek that may have a current. To alleviate this concern, the ORCA-IV is outfitted with a Doppler Velocity Log (DVL) system. This system measures the vehicle's velocity relative to the bottom of the arena. This velocity information is incorporated into the control loop, enabling the vehicle to perform maneuvers such as navigating in a straight line.

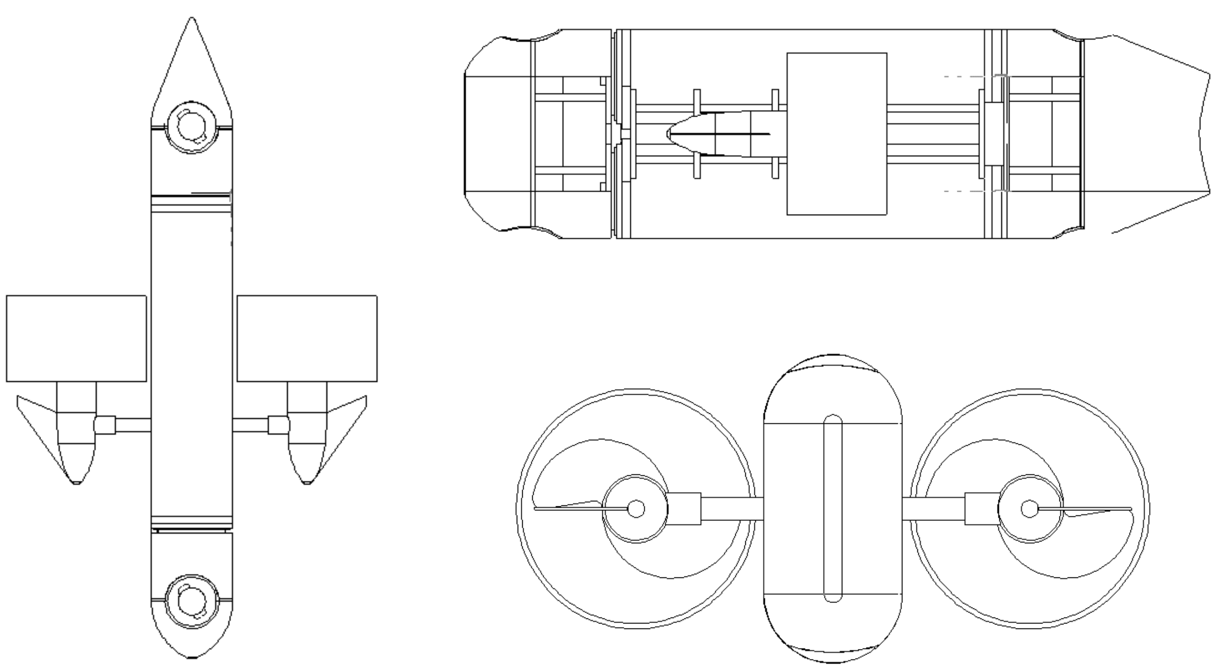

**Figure 1: Mechanical Drawings**

## Mechanical and Electrical Systems

The hull of the ORCA-IV has twin dry compartments that contain the electronic systems. The compartments are made of 15 cm (6-inch) diameter PVC pipes. The tubes are mounted on an aluminum frame and are stacked vertically. A gasketed PVC plate bolts across the stern of each tube. Through-hull electrical connections are made with bulkhead connectors mounted into 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 holds the batteries, motor drivers and power electronics. This particular layout makes the location of the batteries, the heaviest part of the vehicle, as low as possible, lowering the metacentric height and increasing the righting movement of the vehicle. Testing has shown the ORCA-IV to be passively stable in pitch and roll. 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 PVC end plate with a blind-mating multi-pin connector so that it can be removed without disconnecting any cables. The ORCA-IV can be opened in less than 60 seconds with a single wrench.

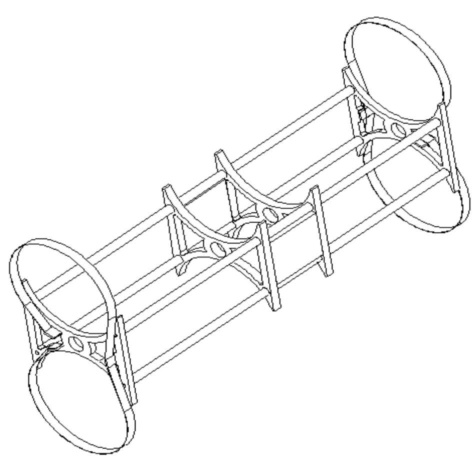

**Figure 2: Aluminum Chassis**

## Bow and Stern Hull Modules

The bow and stern hull modules consist of an aluminum frame, a vertical thruster duct and a streamlined fairing. The fairings are constructed of ABS plastic and are designed to give the vehicle a teardrop-like shape, thereby increasing its hydrodynamic performance and power efficiency. The aluminum frame of each hull module provides a structure to securely attach the onboard equipment. A hinge and latch assembly on each module allows them to open and swing freely, giving easy access to the electronics compartments and connector panels.

## Vertical Thrusters

The vertical thrusters are shrouded with 10 cm (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 7 cm (2.75 inch) RC boat propellers. The thrusters are streamlined with fairings made from PVC to maximize the flow of water through the duct. This design increases thrust and reduces power consumption.

## Main Thrusters

The main thrusters are Minn-Kota reversible electric trolling motors with 25 cm (10 inch) propellers. The motors were chosen for their high power, reasonable cost, rugged design and double O-ring seal. Each motor draws 15 A at 12 V and generates 150 N (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. A 28 cm (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. Four Novak "Super Rooster" FET H-bridge PWM speed controllers drive the motors. Despite their low cost ($100), these units outperformed many OEM motor drivers that were evaluated. The units can switch over 40 A at 12 V, have an on-resistance of less than 2 milliohms, 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 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 are rated to a depth of 80 m. Each outboard component connects to the vehicle using its own connector mounted in the PVC plates 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 Assembly

The ORCA-IV is equipped with a device to recover the barbell-shaped recovery marker. The device is mounted below the bow of the vehicle. It resembles a rake that is 70 cm wide and has large, blunt, forward-facing tines. When making an attempt to retrieve the recovery marker, the submarine will cruise at an appropriate depth so the rake will contact the vertical shaft of the recovery marker. Using the acoustic transmitter and strobe on the beacon to navigate, the vehicle will sweep over the recovery marker. The rake will passively ensnare the recovery marker. Each tine of the rake has a spring-loaded clasp that will allow the shaft of the recovery marker to slide between the tines when the vehicle is moving forward. If the vehicle reverses or turns with the recovery marker captured, the clasps will prevent it from falling out. The rake is designed to be passive and will work with misalignment of up to 35 cm between the center of vehicle and the recovery marker. These features make it possible to grab the recovery marker without precisely determining its position.

## Electronics Cards

The electronics are mounted on slide-out aluminum cards. These cards can be quickly removed from the vehicle for bench-top servicing. The power electronics and fuse box are mounted on one 6" wide, 24" long reinforced aluminum sheet. The batteries are mounted on a similar aluminum sheet that bolts to its underside, forming a single card. This card slides into PVC rails inside the bottom electronics compartment. This arrangement allows the batteries to be swapped for a charged set in the field to minimize interruptions to testing. 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 sensor electronics are mounted in a similar configuration. The top card has a hole pattern drilled into it to facilitate the 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 two 7.2 Ah 12 V sealed lead-acid gel-cell batteries to power the thrusters. A second pair powers the electronics. All systems on the vehicle are designed to be powered with 12 V. Each battery bank 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 40 A mechanical relays. Two external mechanical kill switches with a colored rip-cord can be used to power down the motors or the entire vehicle.

### Monitoring System

The temperature and pressure in each sealed compartment are measured using an LM35 temperature sensor and an ASCX30AN 30 PSIA pressure transducer. The motor and electronics battery currents are measured using two LEM LV25-P Hall Effect Current Sensors. The 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 two sensors allow detection of electrical failure, low battery and water leakage before the vehicle becomes inoperable.

## Sensor Suite

### 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. The 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 a custom acquisition and filtering system was designed. Each sensor's output is appropriately filtered and amplified by laser-trimmed instrumentation amplifiers, and the signals are scaled to the proper 5 V 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 100 ksps 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

A Honeywell HMR3000 Digital Compass is used on the ORCA-IV. This strapdown compass uses solid state magnetoresistive sensors and a fluid-bulb inclinometer to measure heading, pitch, and roll. The unit is accurate in heading to 0.5 degrees and has hard iron compensation features.

## Altimeter

The ORCA-IV uses a PA500 sonar altimeter made by Tritech to measure its distance from the floor of the arena. The sonar transmits pings at a 500 kHz carrier frequency and returns the measured altitude over an RS-232 serial interface. The unit is accurate in the range from 0.1 m to 10 m, suitable for the depth of the competition arena.

## Depth Sensor

A Sensotec TJE series pressure sensor is used to gauge depth. It has a full-scale range of 50 PSIA and a temperature compensated accuracy of +/- 0.12 %. This corresponds to an accuracy of +/- 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.

## Doppler Velocity Log

The ORCA-IV is equipped with a SonTek Argonaut Doppler Velocity Log (DVL). This unit is assembled with a lightweight Delrin housing and was chosen for its low power consumption, small form factor and precision measurement capability. To avoid incorrect readings generated by the wake of the vehicle the DVL is capable of taking measurements in a programmable depth area away from the body of the ORCA-IV. The DVL measures the velocity of the vehicle relative to the bottom, making the ORCA-IV capable of maintaining course in adverse current conditions.

## Passive Sonar System

### Overview

The ORCA-IV includes a passive sonar system to detect and process pings from the 27 kHz acoustic transmitter on the beacon.

The passive sonar unit is mounted at the bottom of the forward hull module. The passive sonar receives pings using four hydrophones, mounted in a square array. The hydrophones are mounted to the bottom of an IP-68 rated waterproof enclosure, which contains processing electronics.

The passive sonar system communicates with the ORCA-IV main computer using an RS-232 serial link. For each ping received, the unit transmits the bearing to the transmitter in degrees, and the time in milliseconds since the last ping. The main computer uses this information to aid in navigation toward the beacon, and to determine the ping rate.

The system finds the bearing to the acoustic transmitter by measuring the time delay between the first arrival of ping energy at each of the four hydrophones. The system assumes that the incident wave of the ping is a plane wave propagating along a straight line from the acoustic transmitter. Using this assumption, it uses trigonometry to calculate the bearing to the acoustic transmitter from the four measured delays.

A classic problem in direction-finding systems is multipath: A ping from the transmitter can arrive along a straight line path, but can also arrive along other paths that include reflections off the boundaries of the arena. The signals arriving along reflected paths arrive at bearings other than the bearing to be measured and can result in spurious readings. The system solves this problem using the straightforward "first arrival" method. Since the shortest path between two points is a straight line, the first ping energy received from the transmitter must arrive along the straight-line path.

## Implementation Details

The system uses four Reson TC4037 probe hydrophones. The hydrophones are mounted at the corners of a square which is 10 cm on a side.

The system has a fully differential analog signal chain. The TC4037 has a bipolar ceramic element, and thus has a differential output. The output from the hydrophones is high-pass filtered to reject DC offset by a single-pole RC filter with a 10 Hz cutoff frequency. Next, it is preamplified using a wideband differential-output instrumentation amplifier, which is made from the two halves of a Burr-Brown OPA2604 FET-input dual operational amplifier. The signal is then level shifted and balanced by an Analog Devices AD8138 low-distortion differential ADC driver. Finally, the signal is passed through a single-pole RC low-pass anti-aliasing filter and fed into an Analog Devices AD9260 analog-to-digital converter.

The AD9260 is an oversampling sigma-delta converter. It samples the input at eight times the desired output word rate, then passes the digitized signal through a decimating FIR filter, thereby increasing the number of bits per sample. Because the actual sampling of the analog signal is done at a rate that is much higher than the output sample rate, a single-pole passive RC filter at the input provides sufficient anti-aliasing. The AD9260 is configured to output 16-bit samples at a 250 kHz rate.

All four hydrophone channels are simultaneously sampled by four A/D converters. The digital outputs from the A/D converters are read by an Analog Devices

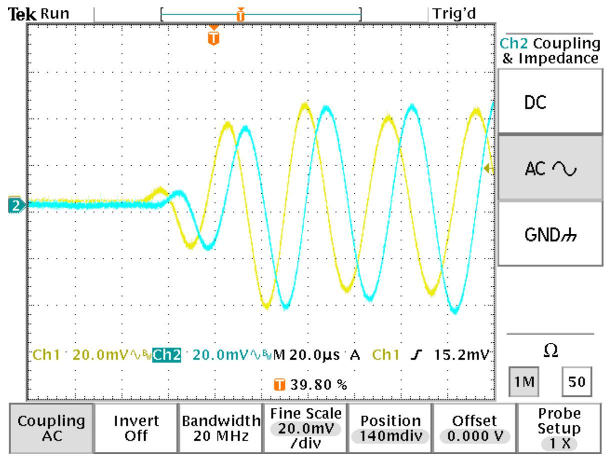


**Figure 3: Signals from a two-element array, showing angle-dependent phase delay.**

ADSP-2189M digital signal processor. The ADSP-2189M is a 16-bit integer DSP which has 128K of on-chip RAM and runs at 77 MIPS.

When a new set of samples is ready, the A/D converters cause a hardware interrupt in the DSP. The DSP stores the sample from each hydrophone in a 512-sample-long circular buffer for off-line processing. It also processes the signal from one hydrophone in real-time to determine if a ping is being received. If the DSP detect a ping, it stops taking data and computes the bearing to the transmitter using the stored data.

To detect pings, the system passes the signal from one hydrophone through a 128-tap lowpass filter with a 27 kHz center frequency and a 1 kHz passband. Next, it rectifies the signal and passes it through a 64-tap decimating FIR low-pass filter with a 1 kHz cutoff frequency. The output from this operation represents the envelope of the input signal. If this signal exceeds a threshold for a specified number of samples, the DSP registers a ping.

Once a ping is registered, the DSP processes the data stored in the four 512-sample circular buffers to calculate the bearing to the ping. Each signal is filtered with a 64-tap FIR bandpass filter with a 27 kHz center frequency and a 10 kHz passband. The system then estimates the time delay between the signals using time-domain thresholding to find a coarse estimate and upsampled cross-correlation over a narrow lag range to refine that estimate. This approach allows the system to use data from many samples to compute a bearing estimate, vastly improving its accuracy and noise tolerance.

For each pair of adjacent hydrophones, the system calculates a bearing estimate to the acoustic transmitter by taking the arcsine of the normalized measured delay. The bearing estimate from each pair of hydrophones includes a front-to-back ambiguity. The system removes this ambiguity by combining the data from orthogonal hydrophone pairs. Once an estimate is ready, the unit transmits it over its RS-232 serial port to the ORCA main computer for navigational use.

## Directional Light Sensor

The directional light sensor uses visible-spectrum enhanced silicon phototransistors with opaque shrouds to enhance directionality. The eight sensors are located in a circular array and are capable of detecting light directionality within a plane. The sensors yield raw data that can be interpolated to gain better than 8-quadrant sensitivity by measuring relative light intensities in all 8 sensors. The data are processed using an SH1 microcontroller and directional data are transmitted via an RS-232 serial link to the ORCA-IV computer.

## Control Computer

All navigation and control code is implemented on a Pentium-based PC/104 embedded computer running Linux. This computing platform provides a stable and familiar programming environment, is amenable to remote operation, has modular standard peripherals and has a small install footprint. The computer uses an 80 MB M-Systems Disk-On-Chip 2000 FLASH disk, in place of a standard mechanical hard drive. The ORCA-IV PC/104 stack consists of the CPU card, a switching power supply, a serial port expansion card and an A/D card to interface to analog sensors. Most sensors and actuators interface to the computer using the RS-232 serial protocol.

## Development

For development and testing purposes a tether can be attached to the vehicle to make communication with the computer possible. The computer uses the Sun RPC protocol to communicate with multiple on-shore computers. From each station the vehicle can be remotely operated with a joystick, and all variables and sensor values can be inspected and modified with a graphical user interface. In addition, the main control program can be remotely modified and recompiled. All of this can be done while the submarine is submerged and operational.

The control program has a simulation mode that uses a simple mathematical model of the pond and vehicle to generate simulated non-ideal sensor data in response to motor commands. The simulator employs a rudimentary graphical user interface and a simplified graphical mock-up of a simulated pond. 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 1 m. Communication with the vehicle can also be established using a tether which provides an Ethernet link to the computer and a live video feed from the CCD camera mounted on the bow of the vehicle. This allows team members to watch what the vehicle is doing while submerged, which has proven useful when debugging complex autonomous maneuvers.

# Mission Strategy

The control code for ORCA-IV is structured as a script that calls a series of pre-programmed autonomous "behaviors" to carry out the mission. These behaviors are maneuvers such as holding a position, navigating straight along a given heading, or driving toward the flashing strobe.

The first objective is to pass through the validation gate. The gate is placed within 6 m of the launch point, so the vehicle will dead-reckon a path through the gate by driving straight on a pre-assigned heading. The vehicle then stops and waits for a ping from the beacon. When a ping is received, the vehicle turns to the heading of the beacon and navigates toward it. The course is corrected each time an additional ping is received. When the vehicle is cruising toward the beacon, the directional light sensor should indicate the strobe is in front of the vehicle once the vehicle is in range to detect the light flashes. The vehicle stays on course until the directional light sensor indicates the strobe is behind the sensor, indicating the vehicle has just passed the beacon. The vehicle immediately stops and uses the compass to turn to the known heading, relative to the beacon, of the array of man made objects. The vehicle then performs a predefined search pattern using dead-reckoning augmented with velocity feedback from the DVL. Depth data from the altimeter and pressure sensor are logged while executing the search pattern for later analysis to find the heights of the objects. After completing the search pattern, the vehicle dives to the appropriate depth to catch the recovery marker with the rake. The vehicle again uses the beacon's pings and flashes to navigate toward it. The vehicle will navigate a path over the estimated center of the beacon using the angle data from the acoustic transmitter and strobe light separately. This pass over the beacon will snare the recovery marker. The vehicle will then return to the launch site by following the heading opposite the original heading it followed to reach the beacon.

# Conclusion

The design cycle of the ORCA-IV has focused on developing mission specific sensors and high-level control code. This is possible because the core platform of the AUV has a modular design that can be adapted to perform various missions. The addition of the DVL to the sensor suite will provide ground-referenced velocity information that should fortify some of the low-level navigation algorithms. By making changes to the systems in set increments, the vehicle is kept in an operational state so it can be tested in the water often. These frequent water tests are a key part of developing the hardware and software systems needed to complete the mission.