ORCA-V: An Autonomous Underwater Vehicle

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The ORCA-V is a fully autonomous submarine built to compete in the 2002 International AUV competition. The ORCA-V is 60” long, 32” wide, and approximately 50 kg. The vehicle is propelled by a pair of forward thrusters mounted on the sides and a pair of vertical thrusters mounted on the bow and stern. The vehicle has a maximum cruising speed of 1.1 m/s. Autonomous navigation is aided by a suite of instruments including a three-dimensional magnetic compass, a water pressure depth sensor, a fluid-bulb inclinometer, a 6-degree of freedom inertial measurement unit for navigation, a DSP based sonar direction finder, a Doppler velocity logger, and an underwater video camera with computer vision software.

The ORCA-V follows the basic modular design philosophy of previous incarnations of ORCA, however, each subsystem has been completely redesigned and constructed with the goal of better robustness and better maneuverability. The main dry hulls have been reconstructed from machined clear PVC for greater depth capability. The motor control electronics has been simplified and integrated for greater reliability; the battery chemistry has been changed to sealed NiMH for greater capacity at a lower weight; the computer has been upgraded to handle image processing; the software has been rewritten in Java with greater modularity and reliability.

The vehicle was outfitted with two side-looking echo sounders for wall following navigation. An extensive data analysis program has been written to allow the operator to efficiently generate a list of barcodes and platform heights for presentation to the judges.

Introduction

The ORCA-V is designed to fulfill the requirements and comply with all the rules of the 5th International Autonomous Underwater Vehicle Competition. The competition arena is located at the SPAWAR TRANSDEC facility in San Diego, California. The arena is roughly oval in shape, with a spherical center area. The spherical area is 160 feet in diameter and 38 feet deep at its center. The oval area is approximately 200 feet wide and 320 feet long. There are 17 platforms varying from 1 to 4 feet in height, each bearing a 1'x 2' barcode. Each of these barcodes represents a number from 0 to 31. The first platform is placed at the deepest point of the spherical area and has an acoustic beacon. The center platform is surrounded by 8 evenly spaced platforms at a 20-foot radius. A second set of eight platforms are placed 10 feet away from the outer wall, 30 degrees apart from each other.

The vehicle is awarded points for accurately reporting the barcode number and depth of each platform. Before the vehicle may complete any part of the mission, it must first pass through a 10'x 6' validation gate, which is placed 10 to 20 feet from the starting point. Our vehicle is designed to complete the mission reliably, repeatedly, and safely under the various water conditions. The modular design allows for relatively easy replacement, testing, or addition of components. To further comply with the spirit of the mission, all of our modules have been designed be tested and operated safely.

Overview

The hull of the ORCA-V is designed to be a modular platform for an electronic payload. Two watertight compartments hold the batteries, the computer, and much of the electronics. Two flooded compartments holds suite of outboard sensors. Two vertical thrusters, housed in ducts at the bow and stern, control the vehicle's depth and pitch. Two horizontal thrusters control the velocity and heading of the submarine.

The vehicle is controlled by a single board computer running Linux. A spread-spectrum radio data link or an Ethernet tether may be used to communicate with the submarine computer.

The ORCA-V controls its depth using feedback from a pressure sensor or sonar altimeter. The can also be used to measure the distance of platforms below the vehicle. Two side-facing sonar range finders can be used to navigate the vehicle at a fixed distance along a wall. Pitch, roll, and direction are controlled using feedback from a three-axis rate gyroscope and a magnetic compass. The submarine can navigate in relation to an acoustic beacon with its four hydrophones. A Doppler Velocity Log system measures the velocity of the submarine relative to the ground. To read the barcodes on the platforms, the ORCA-V has a video camera.

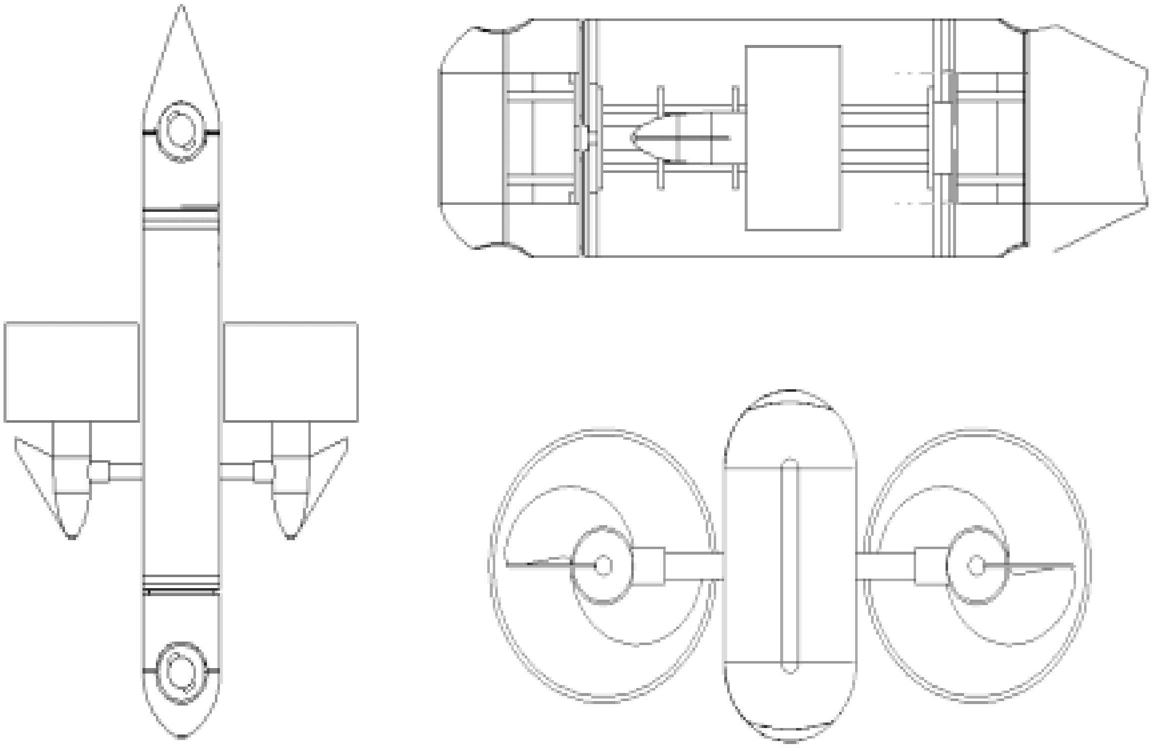
ORCA-V From Above

Mechanical and Electrical Systems

The hull of the ORCA-V has twin dry compartments that contain the electronic systems. The compartments are made of 27-inch long, six-inch diameter PVC pipe. The tubes are mounted on an aluminum frame, one above the other. PVC plugs with double O-ring bore seals are used to close the dry compartments. Through-hull electrical connections are made with bulkhead connectors mounted into these plugs. These plugs allow convenient access to the electronics. The top compartment holds the computer, compass, pressure sensor, inertial sensors, radio transceiver, and antenna. The bottom compartment holds the batteries, motor drivers and power electronics. This electronics layout is designed with the batteries as low as possible, lowering the metacentric height and increasing the righting moment of the vehicle. Testing has shown the ORCA-V to be passively stable in pitch and roll. Each dry compartment holds a slide-out aluminum card, which holds the electronics. 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-V can be opened in less than 30 seconds without tools.

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 tear drop-like shape, lowering its drag coefficient and increasing its power efficiency. The aluminum frame of each hull module provides a structure to securely attach all of the submarine’s



Mechanical Drawings

modules. The frame allows versatility in the way that the modules are configured, and in the number or size of modules attached. A hinge and latch assembly on each module allows the flooded compartments to open and swing freely, giving convenient access to the dry hull compartments and their connector panels.

Vertical Thrusters

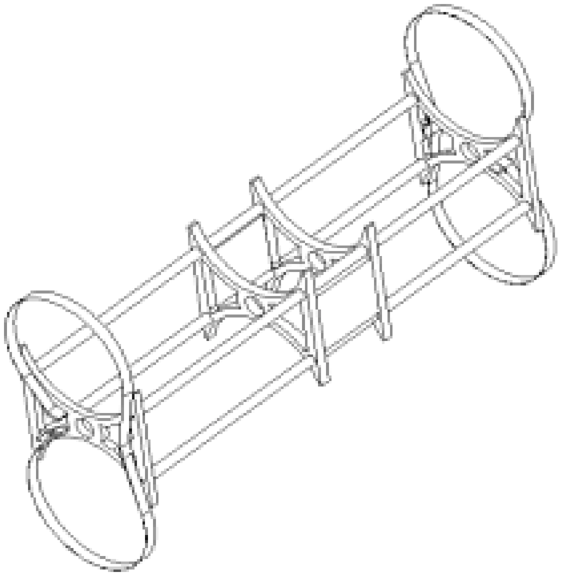
Four-inch ducts mounted in the bow and stern hull modules shroud the two vertical thrusters. The thrusters are made from small DC electric motors, which have been encased in watertight PVC enclosures that can be dismantled for modification and repair. RC boat propellers are used to create the thrust needed to control the submarine's depth. 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 Endura 30 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 fixed around each thruster for safety. The motor mounts have been redesigned and the shrouds have been attached to the submarines aluminum frame for added dynamic stability.

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. A PIC 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.



Hull frame

Electrical Connections

Electrical connections through the hull are made with hermetically sealed locking multi-pin connectors made by W. W. Fischer. The connectors are rated to a depth of 80 m. Each outboard component connects to the vehicle using its own receptacle 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.

Electronics Cards

The electronics are mounted on slide-out aluminum cards for bench-top servicing. The power electronics and fuse box are mounted on one six inch wide, 24 inch long reinforced aluminum sheet. The batteries are mounted on its underside, forming a large single card. This card slides onto PVC rails attached to the insides of the bottom electronics compartment. This arrangement allows the batteries to be easily replaced, so testing time can be utilized more efficiently. All electrical connections from the card to the compartment's stern connection plate are made through a mating pair of ELCON "75A Middle Drawer" back plane 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 pattern of holes 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" back plane connectors.

Power Supply

The vehicle uses a bank of six 3.0 Ah 12V sealed NiMH batteries to power the thrusters, and a bank of four 4.5 Ah 12V NiMH to power the electronics. Each motor, the lamps, and the electronics power supplies are fused for safety. Power from the batteries is switched through a set of International Rectifier IPS5551 ruggedized 100A MOSFET switches. Two waterproof magnetic kill switches with colored ripcords can be used to power down the motors or the entire vehicle.

Monitoring System

A monitoring system measures the power bus voltages, individual motor currents, the electronics bus current, and dry-hull internal temperatures. This information is displayed on the vehicle control console for diagnostic and power management applications.

Temperature is monitored using LM35 temperature sensors, one on the power electronics control board and one integrated with the computer motherboard. Current is measured using a bank of six LV25-P Hall effect current sensors. The motor bus voltage is measured using a LEM LA55-P isolated voltage sensor, to preserve galvanic isolation between the motor and electronics power buses.

Imaging

The ORCA-V is equipped with a machine-vision system composed of an Aurora color video camera made by Insite Tritech and a Sensoray Model 311 PC/104+ frame grabber.

Sensor Suite

Inertial Measurement Unit

The inertial sensor package consists of two Gyration MG100 two-axis piezoelectric tuning-fork rate gyroscopes, and three ADXL50 silicon micro machined 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 0.005 g, a full-scale range of 5 g’s, and a bandwidth of 6 kHz. Both of these sensors provide analog outputs for which we have designed a custom acquisition and filtering system. The IMU is connected to the main computer using an RS-232 serial port.

Compass

The ORCA-V 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 consideration for its location, keeping it distant from any strong magnetic fields generated by the motors and hard drive.

Sonar Range Finders

The ORCA-V uses three Tritech PA500 sonar range finders. One us used to measure the distance to the floor of the arena. The remaining two are mounted on the starboard side and measure the distance to the sidewall during wall following. The PA500 transmits pings at a 500 kHz carrier frequency and returns the measured distance over an RS-232 serial port. The units are operable from 0.1 to 10 m distance, suitable for the size of the competition arena.

Depth Sensor

A Stellar Technologies IT2000 series digital pressure sensor is used to measure depth. It has a full-scale range of 50 PSIA and a temperature compensated accuracy of +/- 0.05 %. This corresponds to an accuracy of +/- 1.7 cm. The output signal is transmitted to the computer over an RS-232 serial port.

Doppler Velocity Log

The ORCA-V 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. The DVL measures the velocity of the vehicle relative to the bottom surface of the arena, making the ORCA-V capable of maintaining course in adverse conditions.

Passive Sonar System

The ORCA-V includes a passive sonar system to detect and determine the bearing to the acoustic beacon on the central platform. The passive sonar unit is mounted at the bottom of the flooded hull module at the bow of the vehicle. The passive sonar detects pings using four hydrophones mounted in a square array. The hydrophones are mounted to the bottom of a waterproof enclosure, which contains processing electronics. The passive sonar system communicates with the ORCA-V main computer using an RS-232 serial port. 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 the navigation of the submarine. The system finds the bearing to the acoustic transmitter by measuring the time delay between the first arrivals 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.

Control Computer

All navigation and control code is run by 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 ORCA-V PC/104+ stack consists of a CPU card, a switching power supply, an eight serial port expansion card, and a frame grabber card. 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 the area. 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. This allows team members to watch what the vehicle is doing while submerged, which has proven useful when debugging complex autonomous maneuvers.

Mission Control Software

The mission control software is implemented as a multithreaded Java program. Each sensor has an associated driver thread that communicates with the device and scales its data into engineering units. An autopilot thread keeps the vehicle's depth, heading, pitch, and speed at desired setpoints. The autopilot uses PID control on the four thrusters to servo the values returned by the pressure sensor, compass, inclinometer, and DVL to the desired setpoints. A mission control thread uses a state machine to navigate the over the platforms so the sensors can gather the required information about them. The state machine to be used is described in detail below. A logging thread records all sensor data to disk, including one downward-looking camera image per second. After the vehicle is recovered, a separate data analysis program is used to analyze the data in the log to extract the platform barcodes and heights.

Mission Plan

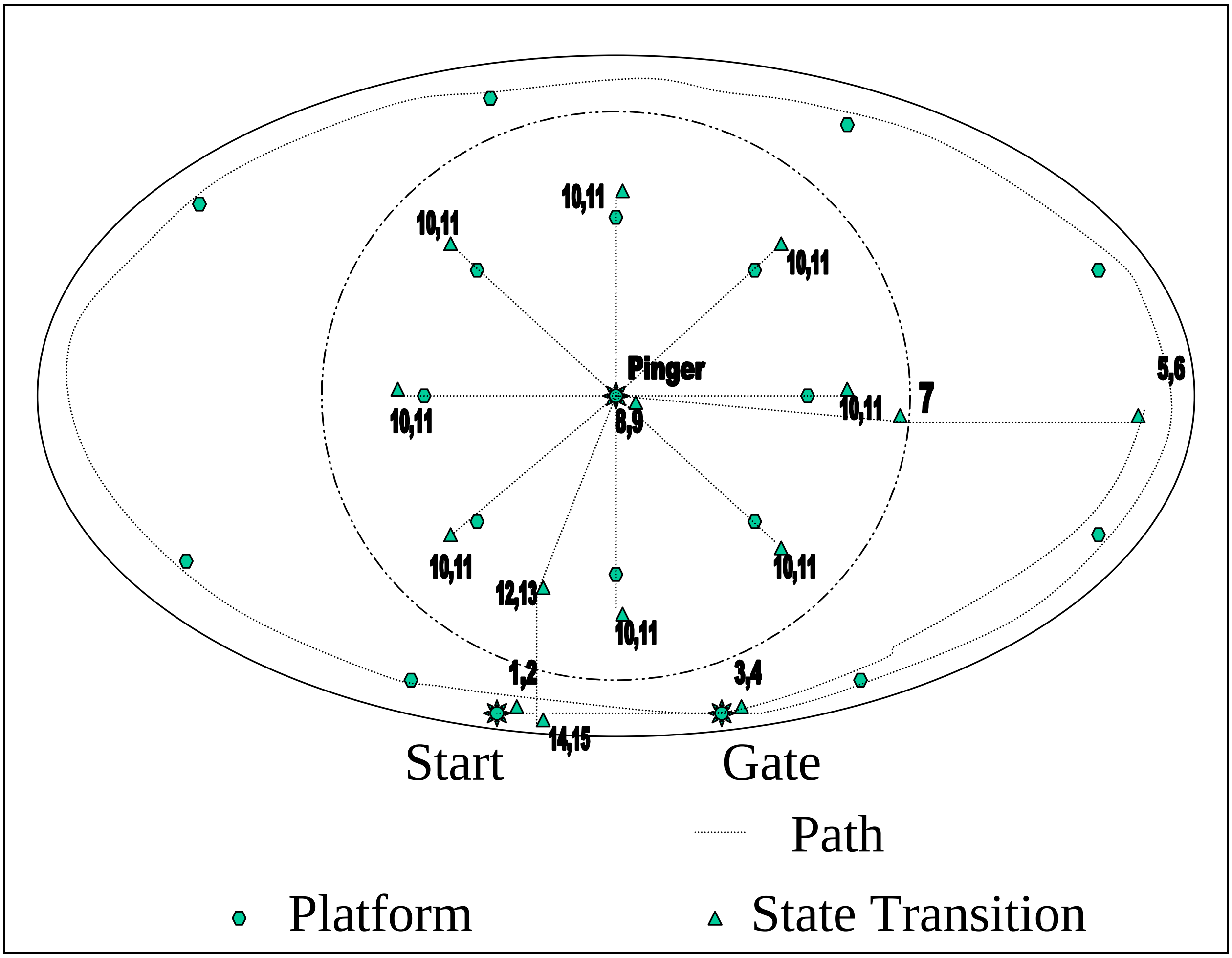
The mission plan is to pass through the validation gate, drive around the perimeter of the pond using wall following, go to beacon at the center of the pond, survey the central ring of platforms in a starburst pattern, and finally, return to the dock.

1. Dive

Upon receiving the radio start signal, the vehicle dives to the pre-set validation gate traversal depth. The termination condition is reaching the desired depth.

2. Drive Through Validation Gate

The vehicle records the current compass heading and drives forward at that heading. The termination condition is the expiration of a timer.



3. Change Depth
The vehicle dives to the pre-set wall-following depth. The termination condition is reaching the desired depth.

4. Follow Wall
The vehicle drives forward along a contour approximately 10 feet inside the wall. The vehicle measures the angle and the perpendicular distance to the wall using the two side-mounted sonar range finders. The termination trigger is armed when the vehicle crosses the due south compass heading. Termination occurs when the vehicle crosses the due north compass heading.

5. Turn to Center
The vehicle turns to face due west. The termination condition is reaching due west.

6. Drive to Center
The vehicle drives forward along a constant (due west) heading in the general direction of the center of the bowl. The termination condition is receiving a valid ping.

7. Drive to Beacon
The vehicle drives forward toward the acoustic beacon under compass heading control. Each time a ping is received, the vehicle adjusts the heading to be equal to the compass heading at the time of the ping plus the bearing to the beacon at the time of the ping.

The termination condition is armed when the beacon is directly in front of the vehicle. Termination occurs when the beacon is behind the vehicle.

8. Dive

The vehicle dives to the bowl operating depth. The termination condition is reaching the bowl operating depth.

9. Drive to Platform

The vehicle drives to a platform, starting at the beacon, along a pre-programmed heading. The termination condition is the expiration of a timer. Each time this state is run a different pre-programmed heading (one of eight, corresponding to the eight platforms) is used.

10. Turn Back Towards Beacon

The vehicle listens for a ping and turns back toward the beacon. The termination condition is the bearing to the beacon reaching approximately zero degrees.

11. Drive to Back Beacon

The vehicle drives back to the beacon, using the same method and termination condition as in state 7. If state 9 has been run less than eight times (i.e. still more platforms to survey) the next state is state 9. Otherwise, the next state is state 12.

12. Turn Towards Dock

The vehicle turns so it faces the pre-programmed heading of the dock (due south). The termination condition is reaching a heading of due south.

13. Drive To Dock

The vehicle drives toward the dock. (due south). The termination condition is the expiration of a timer.

14. Surface

The vehicle sets its forward thrusters to zero and sets its vertical thrusters to full up. The termination condition is the expiration of a timer.

15. Shutdown

The vehicle sets all of its thrusters to zero and awaits recovery.

Data Analysis Software

The ORCA vehicle records time-stamp indexed images and other sensor data and stores them to disk throughout the mission. Once the vehicle is recovered, the operator runs post-processing software that analyzes the data log to determine the barcode values and platforms heights.

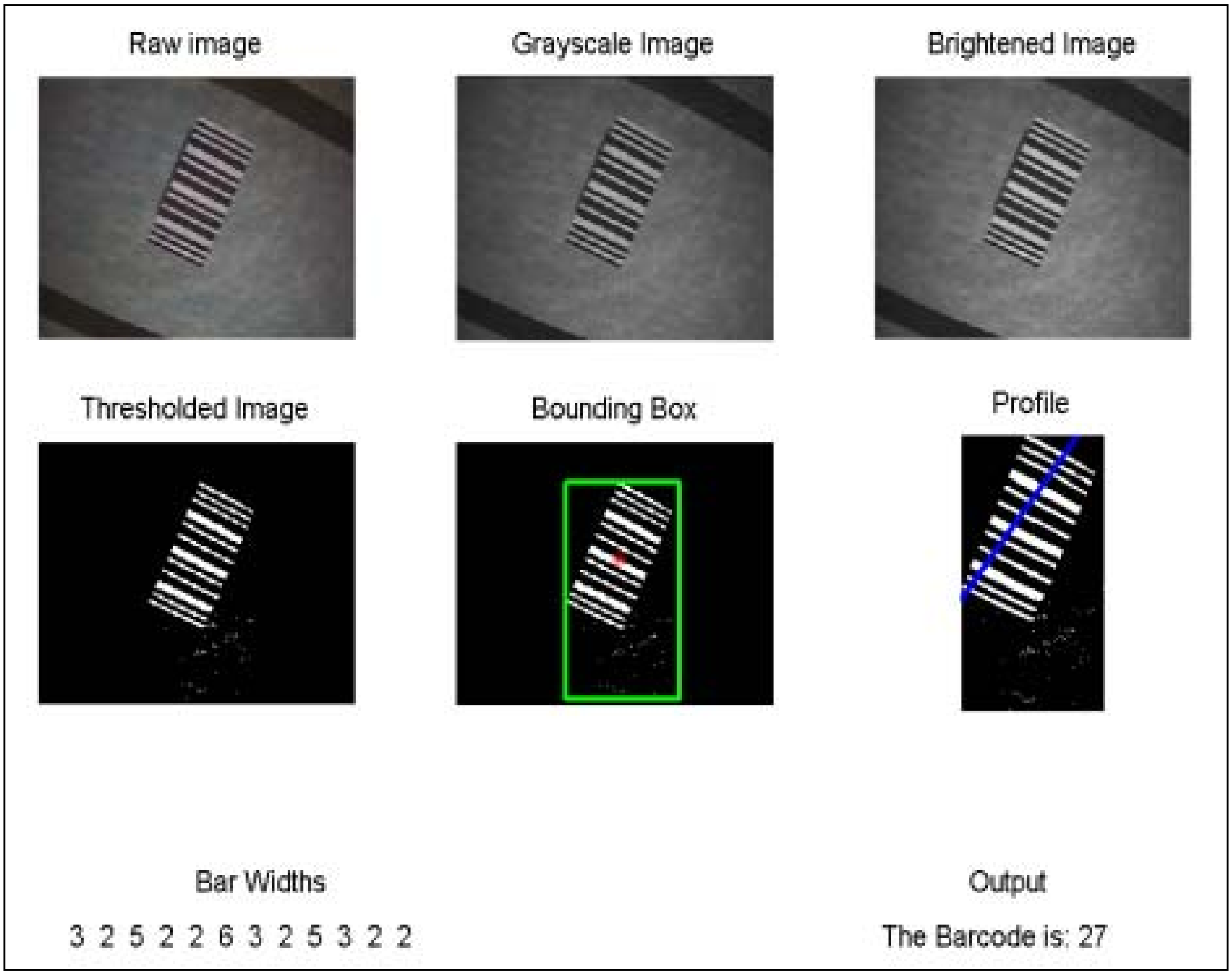
The post-processing operation is illustrated in the figure below. The software reads a color image into memory and converts the RGB component values to intensity values, producing a grayscale image. The image is then normalized so grayscale features span the entire intensity range. The normalization increases the intensity of the white bars in the barcode so that they exceed the preset threshold value. The grayscale image is then converted to a binary image using thresholding, which eliminates extraneous features. A bounding box is generated to enclose the barcode and a profile is traced across the bounding box. The bar widths are measured along the profile and converted to a barcode value. If the profile does not yield a valid code because it does not cross all of the bars, for example, the profile is rejected and another profile is traced at a different angle across the bounding box. This process continues until the barcode is determined or the process times out. The height of the platform can also be determined visually using the measured length of the barcode and the numerical aperture of the camera.

If the operator is not satisfied with the automatically generated data, he can run the graphical data analysis tool. The tool draws a plot of the vehicle track during the mission. The operator can click a particular spot on the track to view a screen of thumbnailed images taken approximately at that location. When the operator sees an image with a platform, he can select it, causing it to be displayed at full resolution. The operator can manually select the edges of the platform, forcing an automated barcode recognition and optical platform height measurement. Any successfully read barcodes are automatically added to the list.

Once the operator is satisfied with the barcode list, he presses the "Print" button, causing the program to print the list of platform heights and barcodes for presentation to the judges.

Conclusion

The 2002 rules present an exciting mission that presents new challenges as compared to previous years. The new mission places increased demands on the vehicle systems across the board, including the hull, propulsion, vision, computer, and navigational systems. We have extensively reconstructed the vehicle to meet these challenges, and look forward to completing system integration and participating in the 2002 International AUV Competition.



3 2 5 2 2 6 3 2 5 3 2 2

The Barcode is: 27