ORCA-IX: An Autonomous Underwater Vehicle

Joshua F. Apgar, Jonathan S. Edelson, Jason Furtado, Ben Howell, Albert Huang, Chris Jackson, Samuel H. Kenyon, Ara N. Knaian, Seth Newburg, Dimitrios Tzeranis, Mehmet Yunt

Massachusetts Institute of Technology

Project ORCA

77 Massachusetts Avenue, Room 4-405

Cambridge, MA 02139

`http://web.mit.edu/orca/www`

Abstract

The ORCA-IX is a fully autonomous submarine built to compete in the 2006 International AUV Competition. The ORCA-IX is 1.27 m long, and masses approximately 45 kg. The vehicle is propelled by a pair of thrusters mounted horizontally on the sides and a pair of thrusters mounted vertically on the bow and stern. The autonomous operation of the vehicle is made possible by a variety of sensors that include a water pressure depth sensor, a state-of-the-art magnetic gyro-compass, a DSP-based sonar direction finder, an inertial measurement unit, and three video cameras supported by advanced machine vision software.

The modular design of ORCA enabled the quick and flexible upgrade of the vehicle based on the specifications of the 2006 competition. The vehicle features a new electronics stack that simplifies the mechanical and electronic connections and improves the performance and reliability of the vehicle. New image processing software and new navigation algorithms enhance the vehicle autonomy and maneuverability.

1. Introduction

ORCA-IX is designed according to the guidelines of the 9th International Autonomous Underwater Vehicle Competition. The competition will take place in the SPAWAR TRANSDEC facility in San Diego, CA, between August 2nd and August 6th 2006. The competition arena is an oval 200' wide and 320' long, with a flat bottom 16' deep.

Figure 1: The ORCA vehicle

The competition arena consists of a validation gate, a Random Order light box, a Docking Station (Station A), a Pipeline Inspection structure (Station B), and a Surface Zone (Station C) marked by an acoustic pinger. Each competing vehicle needs to complete the mission within 15 minutes. Each vehicle must pass through the validation gate before attempting any other portion of the course, read the Random Order Light Box to determine the randomly-selected order of tasks (order of stations to complete) and finally navigate and complete each task at the corresponding station.

ORCA-IX is an upgrade of the successful ORCA-VII and ORCA-VIII vehicles. The ORCA-IX vehicle is designed to complete the mission reliably, repeatedly, and safely. The vehicle's modular design allowed easy testing and modification throughout the process of construction. All of the modules were tested to insure performance, reliability and safe operation.

2. Mission Strategy

Our mission is directed by a pre-programmed state machine for random order sequence task completion. This section outlines the basic sequence of maneuvers the vehicle will use to complete the mission. Figure 2 shows the high level navigation strategy ORCA will use to navigate from point to point in the arena. Arrows indicate the path of travel and the color/line style indicate which sensor will be used for that leg of the mission.

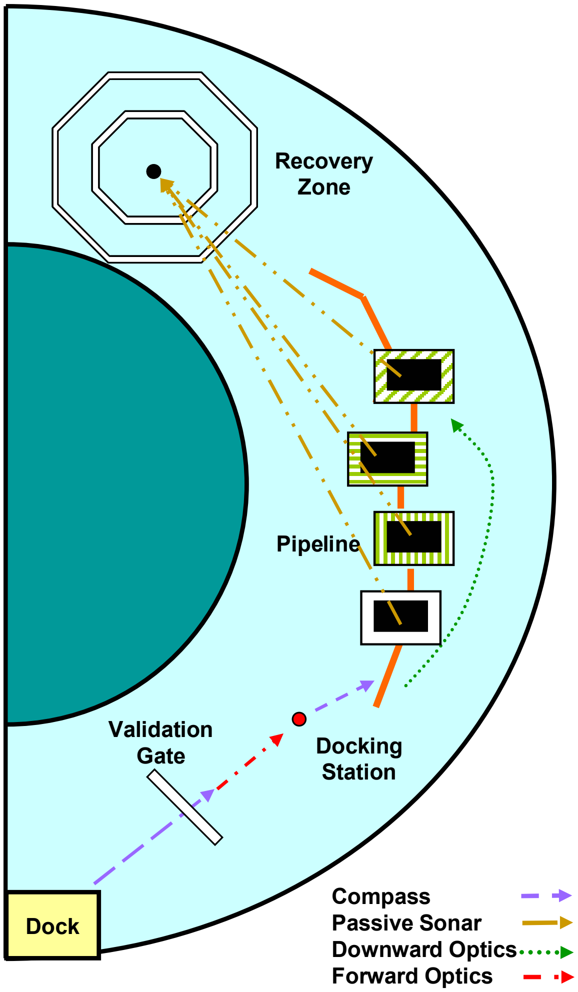


Figure 2: Mission strategy for the ORCA-IX vehicle

Upon activation, the vehicle will dive to a cruising depth of 1.5 meters and will navigate through the validation gate using compass-based dead reckoning. Then the vehicle will detect the frequency and color of the random light box using its forward camera and onboard image processing described in Section 5.

The vehicle will then execute a zigzag shaped search pattern looking for the docking station. When forward optics detects the docking station, the vehicle will home in on the docking station. Docking will be determined by a change in the flash rate. Once the vehicle has docked with the docking station, it will turn towards the pipeline and resume its zigzag search pattern. Once the downward facing optics detects the pipeline, the sub will navigate with feedback information from the vision algorithm that tracks the presence and direction of the pipeline. The vehicle follows the pipeline closely until the image-processing algorithm indicates the presence of the correct bin. The vehicle will then center over the bin and drop the markers.

Finally, the vehicle with turn, adjust its heading to face the acoustic beacon and home in on the acoustic beacon. When the vehicle gets close to the beacon the control software will use the elevation angle to the beacon to determine how close the vehicle is to the center of the recovery zone. As soon as the elevation angle is 90˚ the vehicle will surface ending the mission. The approximate time for the mission is 5 minutes allowing for the possibility of multiple attempts.

3. Vehicle Design

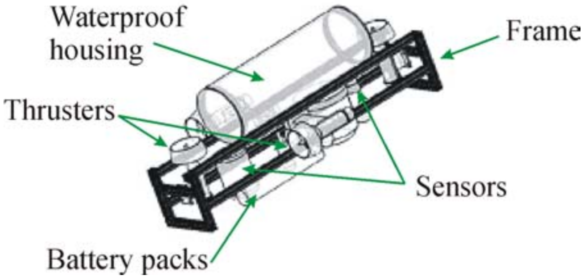


Figure 3: Main parts of ORCA-IX

3.1. Mechanical Design

The main parts of ORCA-IX are the aluminum frame, the waterproof housing (hull), the sensors, the thrusters and the battery packs. The main characteristics of the ORCA-IX design are simplicity and modularity.

The waterproof hull of ORCA-IX has a single watertight compartment and houses the electronics and the computer of the vehicle. It consists of a 27-inch long, eight-inch diameter PVC pipe. The hull is mounted on the aluminum frame and closed with PVC end plugs with double O-ring bore seals. The electronics cards (PC104 stack, motor drivers, power management card) are mounted on guide rails supported by parallel discs that slide inside the hull. The guide rails themselves are mounted into the back end-plug using a stainless steel mounting ring. The interior of ORCA-IX is completely re-designed in order to simplify mechanical and electrical connections and enhance vehicle reliability. Electrical connections through the hull are made with hermetically sealed locking multi-pin connectors, rated to a depth of 80 m. Each outboard component connects to the vehicle using its own receptacle mounted in the PVC end plug at the stern end of the electronics compartment. In addition to the outboard component connectors, there is a tether connector for development and testing.

The aluminum frame consists of the skeleton, the thruster mounts, and the sensor mounts. The skeleton is made of 80/20 10-series T-slotted aluminum extrusions. Modifications can easily be made to the simple rectangular design. The slotted extrusions allow all of the components to slide into place for easy mounting and vehicle trimming. The batteries and sensors are mounted on the aluminum frame in an open sensor bay below the tube. Each one of the four thrusters of the vehicle (two horizontal and two vertical) is mounted on the frame skeleton by a thruster mount, made of three aluminum pieces welded together.

The sensors and batteries are mounted directly on the aluminum frame. This versatile design allows quick changing of the batteries. The batteries are placed low on the vehicle, to increases its righting moment, making the ORCA-IX passively stable in pitch and roll.

ORCA-IX is equipped with a custom-made marker drop mechanism that is comprised of two permanent electromagnets. Each magnet holds one 1.5 inch steel ball bearing marker. When off, the device is a simple magnet that holds the marker in place. When on, the electromagnet creates a field that cancels the permanent magnet's field, allowing the marker to drop. The permanent electromagnets operate on 24V from the motor bus, and weigh about 1 lb. Each electromagnet can be actuated independently. The permanent electromagnet provides power savings over an electromagnet since holding the markers in place, which is the state of the dropper for the majority of the time, requires no power.

3.2. Thrusters & Thruster Drivers

ORCA-IX uses four maneuvering thrusters (Inuktun Services Limited), attached onto the aluminum frame. Two horizontal thrusters allow the control of the vehicle's yaw and surge motions. Two vertically mounted thrusters allow control of the vehicle's depth and pitch motions. Each thruster draws 7 A at 24 V producing approximately 15 lbs of thrust.

The driver circuit for each thruster is based on OSMC modified to satisfy the tight space and low current requirements of the vehicle (http://www.robot-power.com/osmc_info/). The driver design is a simple and robust H-bridge amplifier capable of operating over a wide input voltage range and at rather high currents. An HIP4081 driver chip provides gate drive for the four power MOSFETS of the H-bridge circuit. Various components protect the components from motor transients. The drivers extend OSMC by using Atmel ATmega32 microcontrollers programmed in C, and communicate with the vehicle computer through a serial RS232 bus. The firmware includes an autostop timeout so that the motors stop if control signals cease for 1 second.

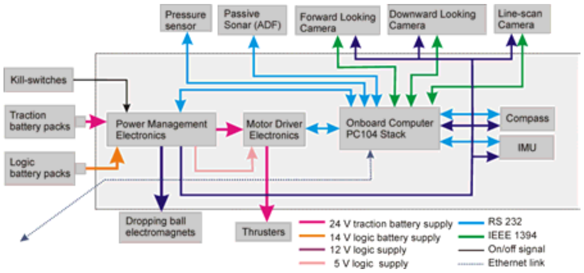


Figure 4: Schematic of the ORCA-IX electronics

3.3. Onboard Computer and Electronics

All navigation and control code is run under Linux on a Pentium-based PC/104+ embedded computer. This computing platform provides a stable and familiar programming environment, is amenable to remote operation, has modular standard peripherals and a small install footprint.

The ORCA-IX PC/104+ stack consists of a CPU card, a switching power supply, two eight-serial port expansion cards, and a Cardbus module. Most sensors and actuators interface to the computer using the RS-232 serial protocol, although the three video cameras are interfaced by a multi-port 1394 FireWire CardBus PCMCIA card (Adaptec FireConnect).

Data can be sent to and from the vehicle via a 100Mb Ethernet data link. During vehicle development, this high speed link allows team members to inspect mission data in real time including streaming video. Sensor data acquired during the vehicle operation can be stored in the 60GB hard drive for post-processing. This feature has proven invaluable when debugging complex autonomous maneuvers.

In addition to the onboard computer, ORCA-IX uses custom printed circuit boards made of small surface mount components, which reduce fragile point to point wiring, and enhance vehicle reliability. They include power management and sensor interface electronics.

3.4. Power Distribution and Monitoring

Two separate voltage busses power ORCA IX—one for the motors and motor drivers, another for the computer, electronics and sensors. Devices on these busses are individually fused to prevent an isolated failure from bringing the whole system down. Efficient boost and step down converters provide all voltages other than the battery voltages. Power from the batteries is switched through a set of mechanical relays. Two waterproof magnetic kill switches with colored ripcords can be used to power down the motors or the computer.

The batteries are sealed in external battery pods that attach to the vehicle via through hull connectors. The electronics battery consists of two battery packs placed in parallel. Each battery pack has 4 Li-Ion cells (2.3 Ah) providing 14.8 V nominal. This new Li-Ion pack enhances the autonomy of ORCA-IX compared to using the old NiMH pack. The motor battery pods have 20 NiMH SCU3300 cells wired in series giving a nominal voltage of 24V and a capacity of 3.3 Ah. A pair of motor battery pods powers the motors for a half hour to an hour depending on use. The use of external battery pods has the advantage of allowing the batteries to be changed much more quickly than if they were housed in the dry-hull.

The vehicle is equipped with a power monitoring PCB that reads the voltage and current provided by the battery packs, and uses a PIC microcontroller to report them to the onboard computer using a RS-232 serial interface. The monitoring system also includes a temperature sensor to alert the operator about over-temperature conditions. Blown fuses are signaled with LEDs for fast identification.

4. Sensors

4.1. Imaging Sensors and Optics

The ORCA-IX is equipped with three video cameras: two Prosilica EC750C color area scan video CMOS cameras - one pointed forward and one pointing downward- and one grayscale line scan camera pointed forward.

The Prosilica EC750C cameras are mounted in individual underwater housings made for easy field reconfigurability. These cameras allow the exposure time and gain to be set in software, making them particularly suited to machine vision applications. Images from these cameras are sent to the computer (PC/104+ Cardbus module PCM 3794) using the IEEE1394 protocol. Machine vision algorithms running on the main computer analyze the images and provide real-time targeting information to higher-level control programs.

ORCA-IX is also equipped with an off the shelf line-scan camera (ISG LW-ELIS-1024a-13194, Imaging Solutions Group, Fairport, NY). This sensor aims to detect and track the docking station light, and is used in conjunction with the forward color video camera to read the Random Light Display signpost. Custom-made telecentric optics are used to focus light onto the imaging sensor. This design provides about 6 deg field of view in the vertical plane, and about 60 deg field of view in the horizontal plane. This camera returns 512-pixel grayscale lines to the main computer via Firewire at 20 kHz and at 14 bits-per-pixel, values sufficient to demodulate the docking station's high and low frequency modulation in software. The line scan camera is mounted on the front of the vehicle in a custom made housing.

Figure 5: ORCA-IX Prosilica EC750C camera

4.2. Acoustic Sensors

The ORCA-IX employs three acoustic elements. Two sonar range finders for navigation and obstacle avoidance, and one passive sonar that can be used to locate acoustic sources such as the pinger in the recovery zone.

ORCA-IX uses two Tritech PA500 sonar range finders. The first range-finder is used to measure the distance to the floor of the arena. The second is mounted on the starboard side and measures the distance to the sidewall for collision avoidance. PA500 measures distance by actively pinging at 500 kHz and measuring the time delay to the echo return. It returns the measured distance to the vehicle computer through an RS-232 serial port. The units are operable from 0.1 to 10 m distance, suitable for the size of the competition arena.

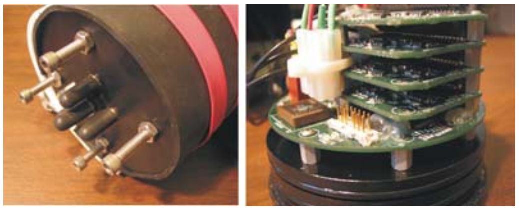


Figure 6: ORCA-IX passive sonar system

The ORCA-IX includes also a passive sonar system to determine a bearing to the Surface Zone acoustic pinger. The passive sonar unit is mounted to the 80/20 frame with a neoprene cover for acoustic decoupling from the frame. This acoustic system detects pings using four hydrophones mounted in a pyramidal array. The hydrophones are mounted to the bottom of a waterproof enclosure, which also contains the necessary processing electronics. The system communicates with the vehicle computer through an RS-232 serial port. For each ping received, the unit transmits the bearing and elevation angle to the transmitter in degrees, the frequency of the ping, and the time in milliseconds since the last ping. The system computes the angle to the pinger by measuring the time delay between the ping signal as received at each of the four hydrophones. Each hydrophone signal is digitized and sampled by a DSP microcomputer. The DSP applies bandpass filters and thresholds the signal from one of the hydrophone to find the start of each ping. The system captures the next 2 ms of signal from each hydrophone for further processing.

4.3. Navigation Sensors

ORCA-IX is equipped with three navigational sensors: a magnetic compass, an inertial measurement unit (IMU), and a depth sensor.

A state-of-the-art True North Revolution GS gyro-compass provides measurements of the submarine heading, roll and pitch angles, as well as the vehicle angular velocity at 28 Hz. It replaced the magnetic compass used previously (Honeywell HMR3000) in an attempt to provide better maneuvering performance in dynamic conditions.

A custom-made inertial measurement unit (IMU) is used to provide measurements for the linear acceleration and the angular velocity of the vehicle. The design of the IMU is based on solid-state Analog Devices MEMS accelerometers and gyros. The angular rate measurement is integrated to give a second measure of heading, roll and pitch. This information is combined with the compass data using an Extended Kalman Filter.

A Sensotec TJE series analog output pressure sensor measures the depth of the vehicle. A PIC microcontroller provides analog to digital conversion and communications to the main computer through a RS-232 serial interface.

5. Software

The ORCA Runtime is a multithreaded Java server that controls ORCA vehicle. The software consists of three layers. At the bottom, the device layer interfaces with the various sensors and performs low-level data integrity checking. The middle layer is a message passing system that abstracts communications between the various software components. The top layer is the command and control layer that interprets the various messages and makes control and strategic decisions. Cutting across these layers is a management framework that provides lifecycle management, logging, and remote management and debugging capabilities to all of the software components.

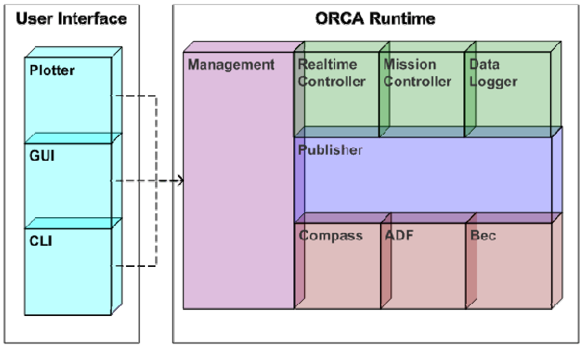


Figure 7: ORCA Software Architecture

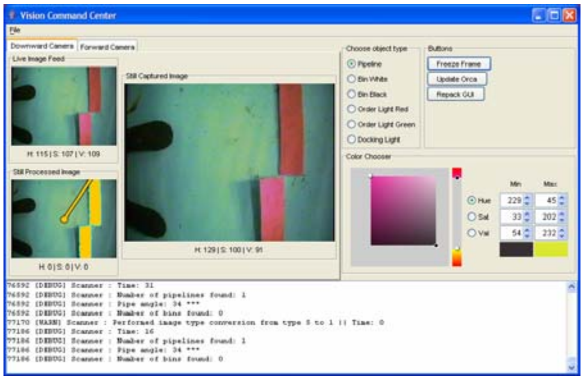
5.1. Control Software

The control of ORCA is broken up into Real Time and Strategic Tasks. The real time controller implements the closed loop go motor functions such as holding a depth. The controller listens for events such as depth changed events and adjusts the four thrusters using a PID algorithm to maintain the desired set points. The Real Time controller supports depth control, altitude control, heading control, velocity control, and pitch control. The higher-level behaviors are implemented by the Mission Controller. The Mission controller has a set of abstract behaviors that connect one of the sensor streams to one or more of the low-level control behaviors. For example, homing in on the pinger is achieved by turning on heading and depth control and by changing the heading set point each time a new ping is detected. Likewise pipeline following control is implemented by adjusting the heading set point to match the angle reported by the vision software. The result of this decomposition is a wide range of behaviors implemented by a relatively small number of primitive control strategies.

5.2. Pipeline and Detection/Tracking

The goal of the pipeline vision system is to capture and analyze images of the pond bottom and determine the existence, position, and orientation of both the pipeline and the pipeline “breaks” which are marked by the four different bins.

The vision software is broken down into three steps: segmentation, recognition, and measurement. In the first step, the image is segmented into regions using color based segmentation. This is efficiently implemented as RGB lookup table that was generated using statistical data from images of the various objects. Sets of connected pixels are gathered into point sets. The second step of the processing determines which (if any) of the objects the point set corresponds to. This process is performed using Geometric Hashing which uses rotation and translation invariant metrics to determine with type of object the point set corresponds to. For efficiency, algorithm is implemented using a lookup table, which can be precompiled. In addition to being efficient, Geometric Hashing is robust to errors during the segmentation step as well as objects being occluded or only partially in the frame. Finally, in the measurement step the recognized is measured for various properties needed by the control behaviors. For example the software determines the center of each object as well as the orientation using been recognized as a one of the four bins or a section of pipeline we measure the center and the orientation of the object by least squares fitting the object prototype from the Geometric Hashing database to the point set.



Choose object type: ● Pipeline

	Min	Max
● Hue	229	45
○ Sat	33	202
○ Val	54	232

```
76592 [DEBUG] Scanner : Time: 31
76592 [DEBUG] Scanner : Number of pipelines found: 1
76592 [DEBUG] Scanner : Pipe angle: 34 ***
76592 [DEBUG] Scanner : Number of bins found: 0
77170 [WARN] Scanner : Performed image type conversion from type 5 to 1 || Time: 0
77186 [DEBUG] Scanner : Time: 16
77186 [DEBUG] Scanner : Number of pipelines found: 1
77186 [DEBUG] Scanner : Pipe angle: 34 ***
77186 [DEBUG] Scanner : Number of bins found: 0
```

Figure 8: ORCA Vision GUI

5.3. Docking Station and Random Order Light Box Detection

The purpose of the blinking light detection sub-system is twofold: to find/track the Docking Station's omni-directional red LED and output a bearing to it, and detect and analyze the Random Light Display signals at the beginning of the match. By detecting the location of the center-of-mass of modulated light on the linear image, the main computer can compute a bearing to the docking station. By determining the modulation frequency of the light, the computer can determine whether the docking station has been knocked over. Finally by using the color information around the detected modulated light the color bit of the random order light box can be determined.

ORCA is equipped with two different sensors for detecting modulated light sources. A color 2D camera that captures frames at 64 Hz, and a grayscale 1D camera that captures frames at 1024 Hz. The line scan camera has the advantage that is has much higher sampling rate and better dynamic range. The conventional camera has a wider field of view as well as color information. Using these systems in tandem provides a robust way of detecting modulated light sources in the near and far fields.

The image processing from both of the systems proceeds in a similar way. Images from both sensors are digitally demodulated to detect either the high or low frequency carrier signals. This demodulation is implemented using a sliding Goertzel DFT (Discrete Fourier Transform) algorithm.

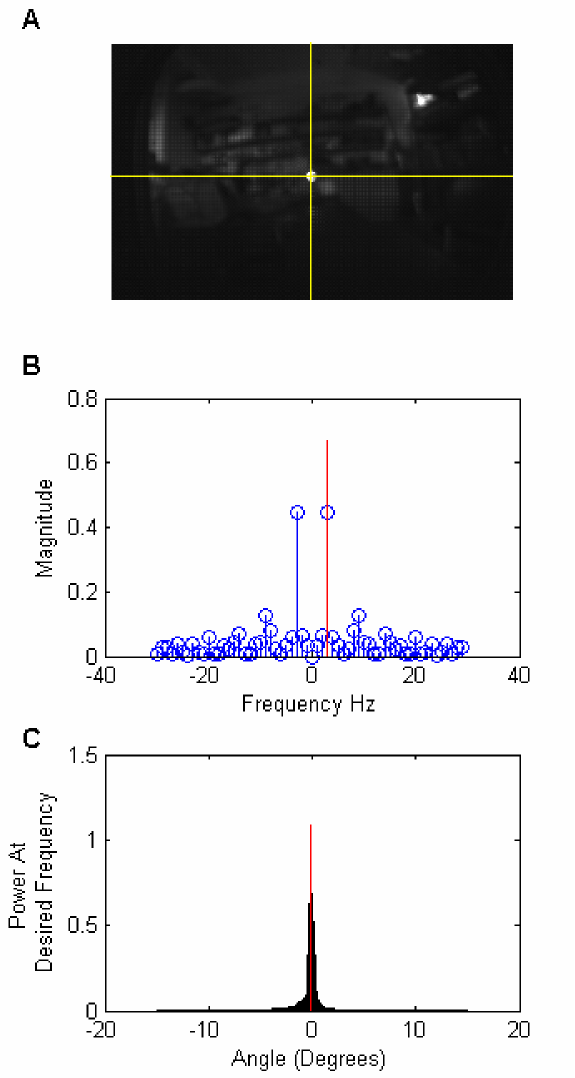


Figure 9: Frequency Based Image Processing

This filter computes coefficients for specific DFT bins centered on N-spaced frequencies of interest. The N-point windows for each pixel are re-processed every input sample, making use of the already-processed spectral components through DFT shifting. This allows us to get coefficients at any time, although we don't need the coefficients every sample so we re-compute the needed coefficients (optimized for magnitude) every 1-10 frames. There is an initial small startup period of N frames establish the window, which can be reset in the case of saturation. The filter gives us magnitudes at the frequency of interest, e.g. 3 kHz, which is compared to a threshold to determine if the frequency is indeed present. This software module outputs a heading of the object based on the pixel index of a detected signal.

For the random order light box detection the color of the center of mass of the modulated signal is determined by generating a histogram the pixels around the peak intensity and choosing the most popular color.

5.4. ADF Signal Processing

To determine the ping frequency, the system calculates a 2048-point FFT of one of the signals, and finds the maximum energy bin. The system then determines the time delay between each pair wise combination of hydrophones, using the method of generalized cross-correlation as described in Underwater Signal and Data Processing by Joseph C. Hassab. The system uses only the first 150 microseconds of ping energy to determine the hydrophone pair delays, to reject multipath echoes.

To find the bearing and elevation angle to the pinger, the calculated delays are used to solve a system of simultaneous equations that gives the required angles in terms of the delays. The system of equations is overconstrained, so the program computes a least-squares optimal solution. The equations are derived from the geometry of the hydrophone array and the plane wave approximation. The calculations for each ping take about 80 ms. Once processing is complete, the bearing, elevation angle and frequency for the ping are transmitted to the main computer in an ASCII string for navigational use.

5.5. Physics Simulator

To test the mission software we have developed a complete simulation of the vehicle as well as the competition arena. The simulator is able to simulate all of the sensor data -including the cameras- and effectors of ORCA. The simulation mode allows control code and algorithms to be developed and debugged in the lab before being tested on the actual vehicle and/or in the water, and has significantly decreased the time needed to bring new features online.

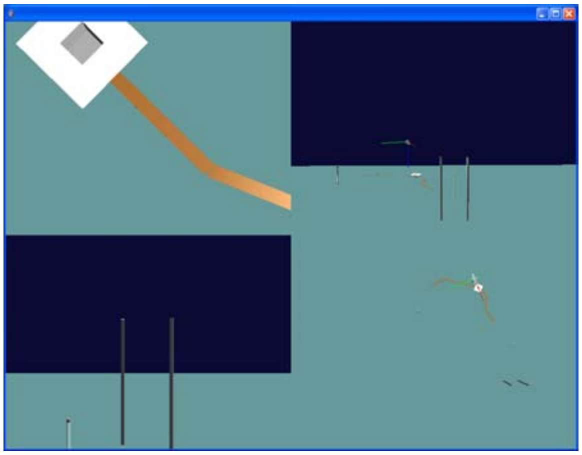


Figure 10: ORCA Simulator

5.6. Remote Debugging and Data Logging

For development and testing purposes a tether can be attached to the vehicle to make communication with the computer possible. The computer uses Java RMI (Remote Method Invocation) 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 is possible while the submarine is submerged and operational.

6. Conclusions

The new ORCA-IX vehicle combines simplicity, reliability and new imaging and navigation capabilities. After the modifications and testing, we look forward to participating in the 2006 International AUV Competition.