Team Blackfinn
Embry-Riddle Aeronautical University
Autonomous Underwater Vehicle

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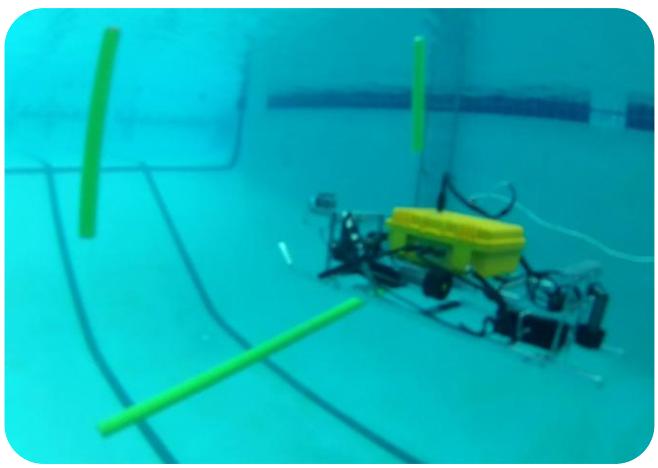

Abstract

This journal paper describes the fully autonomous underwater vehicle BlackFinn developed by Embry-Riddle Aeronautical University to compete in the 2012 RoboSub Competition hosted by the Association for Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR). Team BlackFinn has taken the experiences of previous AUVSI competition teams at Embry-Riddle (including IARC, IGVC, RoboBoat, and SUAS), along with past RoboSub competitions, and applied the knowledge gained to the new AUV system designed. The resulting design to compete in the 2012 RoboSub "Ides of TRANSDEC" challenge includes an improved AUV platform, robust and reliable obstacle navigation, and effective mechanisms for task completion.

1. Introduction

The Robotics Association at Embry-Riddle is pleased to present BlackFinn, a newly designed AUV system competing in the 14th Annual International RoboSub Competition to be held in San Diego, California at SPAWAR Transdec facility. The competition's goal is to develop an autonomous system capable of completing tasks which simulate realistic missions.

Considering the ambitious set of challenges in the "Ides of TRANSDEC", the goal of the Blackfinn team is to reliably navigate through the Validation Gate with a fixed heading, follow the direction of the blaze orange Path Segments and complete each of the Training Area, Obstacle Course, Gladiator Ring, Et Tu Brute, Feeding the Emperor and the Laurel Wreath tasks. The final design of the Blackfinn includes a stable, maneuverable AUV platform, a safe and reliable power and propulsion system, an array of sensors and a powerful on-board processor. The BlackFinn team consists of graduate and undergraduate students representing different majors from the College of Engineering at Embry-Riddle Aeronautical University.

This year's vehicle has been re-designed with a focus on improved performance and weight reduction. All hardware, electronics, and software are new this year.

2. Hardware and Electronics

The main objective for 2012 is to improve the quality, usability, and reliability of the overall system. BlackFinn's design was carefully planned, focusing on system integration, safety, light weight, reliability and maintainability.

Numerous improvements were made over the system fielded by Embry-Riddle at the 2011 competition. The new design includes tools and affordances aimed at fulfilling a majority of the overall mission objectives. Improvements include the integration of a marker dropper, torpedo and launcher and a Laurel Wreath capture mechanism.

2.1 Hull and Frame Structure

The Blackfinn vehicle platform has been redesigned with a focus on reduced weight and overall mission performance. Figure 1 shows the structural aluminum frame that serves as a mounting location for the electronics case and six Seabotix thrusters. The aluminum extensions on the right and left side of the picture serve as convenient carrying handles. Note that the handles on the left (front) are angled up and also serve as a simple capture mechanism for lifting the Laurel Wreath. The exterior of the Pelican Storm IM2200 Case electronics enclosure is shown in Figure 2.

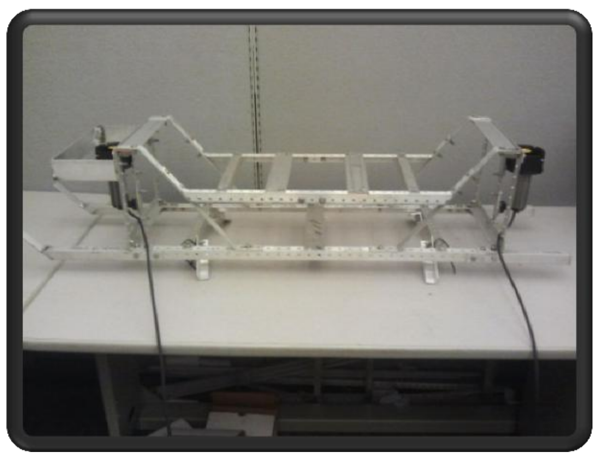

Figure 1: Left-Side View of the Vehicle Frame

The Pelican case is watertight at competition depths and has internal dimensions of 15 by 10.5 by 6 inches. This results in a volume of 950 in^3, which equates to a buoyancy of 34.3 pounds in fresh water.

Figure 2: Watertight Case

The Blackfinn design features a lower center of gravity (COG) than previous vehicles to improve static stability. The low COG is accomplished by placing the buoyant Pelican case near the top of the frame while adding ballast near the bottom of the frame. The simple arrangement eliminates the need to actively control vehicle roll.

2.2 Internal Layout

As shown in Figure 3, the electronic components are all placed inside of the watertight Pelican Storm IM 2200 case.

Figure 3: Internal Layout

All other components are fastened directly to the frame. Placement of components is carefully determined to help maintain the vehicle's static and dynamic stability. The internal electronics are packaged together and secured in the Pelican case using VELCRO® Brand Industrial Strength Hook and Loop Closure System. This provides a secure mounting and easy access to all components for serviceability.

2.3 Thrusters

BlackFinn uses a 6-thruster configuration that provides control over five degrees of freedom (3 translations, pitch and yaw). Inherent roll stability is ensured by placing the center of buoyancy above the center of mass, as described in section 2.1. The thrusters are placed in differential pairs and work in concert to control motion. Additionally, the thrusters are approximately positioned in a common plane so that each pair is decoupled from the others in terms of applied force and moment.

As shown in Figure 4, the two forward/reverse thrusters are attached to the side of the frame near the center of gravity to provide a zero-radius-turning capability. The thrusters in the z-direction allow the sub to climb or drop. The remaining two thrusters directed sideways allow for BlackFinn to strafe and yaw for precise heading control. A custom motor control board allows all six thrusters to be controlled simultaneously.

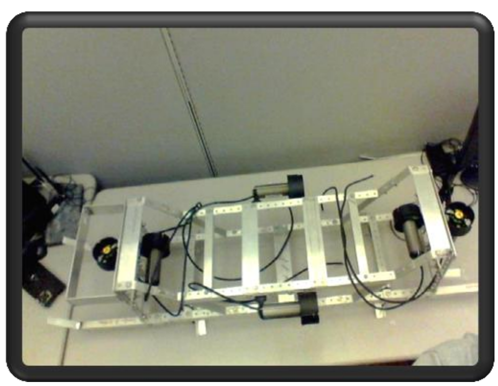

Figure 4: Frame Showing Thruster Locations

2.4 Connectors

The vehicle uses deep sea rated in-line and bulkhead connections from SubConn to communicate with all of the external components and to provide power to the thrusters. The devices connected are: six thrusters, two cameras (through USB), Ethernet, and external power supply. The thrusters are connected using two contact pins, while both cameras use 5 pin USB connectors. All connectors are rated to a depth of 150 meters.

2.5 Camera Mounting

BlackFinn uses two GoPro HERO HD cameras for vision. Each camera provides a 170 degree horizontal and 127 degree vertical field of view. Each camera is mounted in a waterproof GoPro HERO Stereo vision case designed to hold two cameras. The cases are modified to accommodate a cable tethered to the electronics box. The extra case volume that normally accommodates the second camera is needed for cables and connectors. The NTSC analog output signal of the camera is converted to USB using a Hauppauge external tuner mounted in the electronics box. The GoPro cameras provide the AUV with sufficient resolution with an update rate of 15 Hz. Both cameras are statically mounted to the exterior of the AUV, with one facing forward and the other downward.

2.6 Grabber, Dropper and Torpedo

Angled grabber arms on the front of Blackfinn are used to capture the Laurel Wreath. The vehicle will position itself level, align with the center of the wreath, and then move forward. Once the arms are inside the wreath, the vehicle will use its vertical thrusters to raise the wreath to the surface within the octagon.

Two markers and two torpedoes are deployed using a servo and magnet mounted inside the waterproof electronics case. The magnetic field holds markers and torpedoes firmly to the bottom of the case. When Blackfinn is aligned above the correct Gladiator Ring box (as determined by the vision system) the servo retracts the magnet from the bottom of the case, releasing a marker. The torpedoes are released in a similar way, except that a magnetic reed switch inside the torpedo is activated with the release. This energizes an electric propulsion system that carries the torpedo through the Et Tu Brute target holes. The design for the markers to complete the Gladiator Ring task is shown Figure 5.

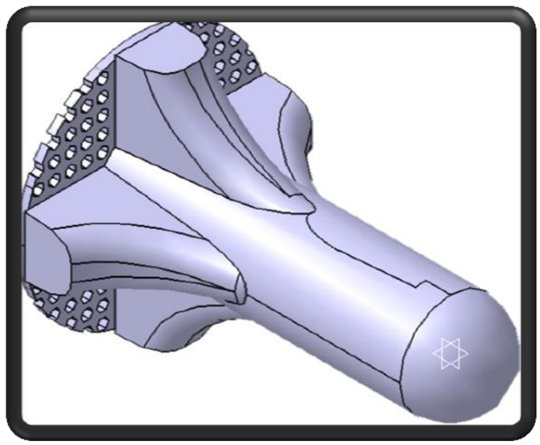

Figure 5: Marker System Design

3. Electronics

The electronics of the sub include both Commercial-off-the-shelf (COTS) components and custom-developed components. Custom designs were necessary in some cases to meet size, efficiency and performance requirements not available in COTS components. Figure 6 shows the fully integrated and packaged electronics cluster.

Figure 6: AUV Electronics Cluster

3.1 Computer

A custom computer was built using off-the-shelf components including an Intel 35W dual-core Sandy-Bridge CPU, 8GB RAM, Solid-State Hard Drive and a PICO-PSU power supply. This system is compact, powerful, and is consumes and dissipates minimum power. A custom power distribution board, shown in Figure 7, converts the battery voltage to a regulated 12V for the computer and other electronics.

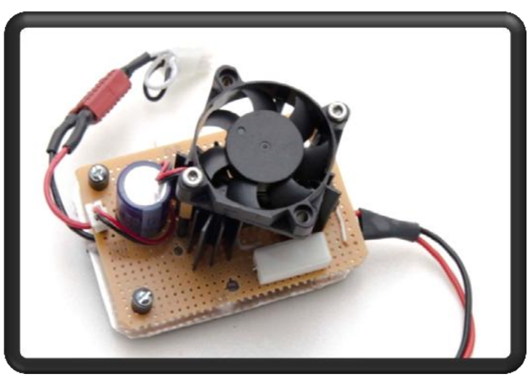

Figure 7: Computer Voltage Converter

3.2 Sparton AHRS

A Sparton GEDC-6, shown in Figure 8, attitude heading reference system (AHRS) is used to provide heading and orientation information. It provides 3D absolute magnetic field measurement and full 360° tilt-compensated heading, pitch, and roll data. Proprietary adaptive algorithms provide accurate, in-field calibration, even in the presence of magnetic distortions due to ferrous objects positioned on the mounting platform. Further, the GEDC-6 has a built in magnetic model of the world.

Figure 8: Sparton Compass

3.3 GoPro Computer Vision Cameras

One of two identical GoPro camera systems used for computer vision is shown in Figure 9. One camera looks forward and one camera looks downward. Each camera has a 170 degree field of view and a maximum resolution of up to 1920×1080.

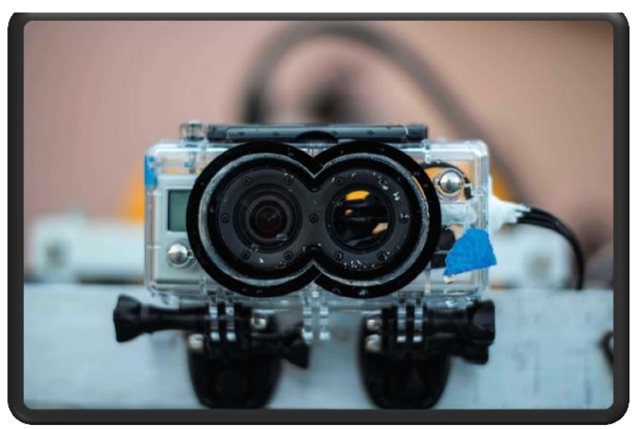

Figure 9: GoPro Camera in Waterproof Case

3.4 Main Interface Board

The board, shown in Figure 10, serves a number of functions, including communication with the computer over RS232, display of vehicle status (temperatures, voltages, etc.), basic menu navigation, and communication with sensors, including the IMU, battery monitor, drive servos, and control status LEDs.

It was custom designed for use with the sub, and integrates many functions that would otherwise require numerous subcomponents and wiring.

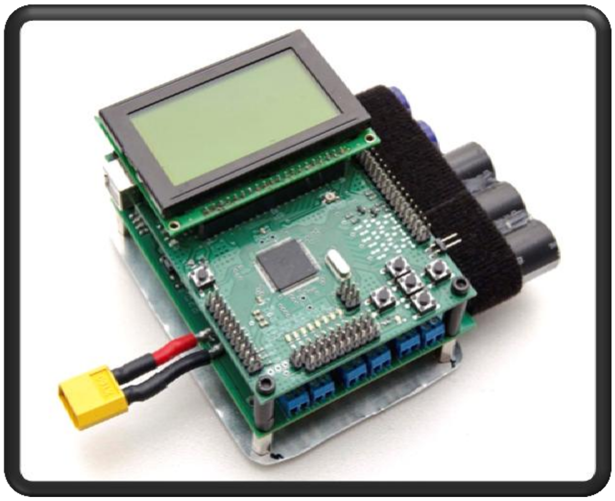

Figure 10: Main Interface Board

3.5 Motor Controller Board

The motor controller board in Figure 11 functions as a controller for each of the 6 SeaBotix motors and as a power supply for the marker and torpedo drop servos. It was custom designed to output up to 15A continuous on each of the 6 bi-directional thruster channels and up to 6A at 5V for driving servos. The board requires input battery voltage between 12 and 40V.

4. Software and Controls

The three primary software packages used on Blackfinn are Python 2.7, QT, and OpenCV. The Python scripting language was chosen as the primary development tool because it is easily readable and fast.

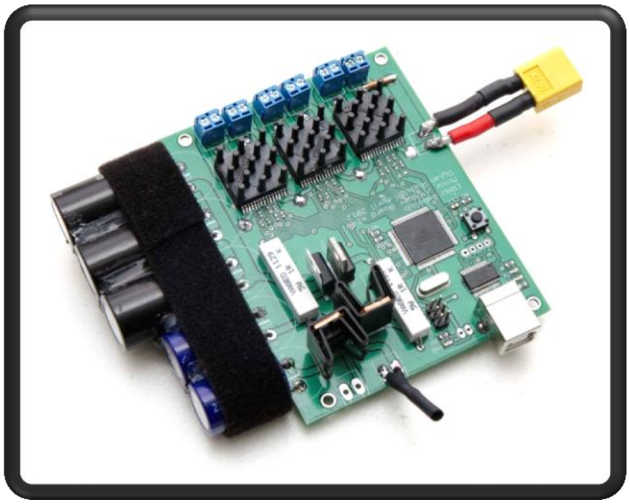

Figure 11: Motor Controller Board

It is used as the backbone for all interface, navigation, and computation functions. QT (with Python bindings) is used for graphical interface with the user. OpenCV (with Python bindings) is used to perform most computer-vision computations. An Arduino IDE and Bootloader are used for microcontroller-level functions. Everything was developed on a Windows 7 (x86-AMD64) computer.

4.1 Rationale

Python was selected for the following reasons:

- Development time is comparatively fast (with respect to traditional, compiled languages).
- The scripts written are inherently readable (and thus transferrable through the competition years) by the nature of the language.
- Moderate run speed is “good-enough”.
- Open-source and cross-platform
- No compiler required

QT was selected for the following reasons:

- QT is a well-established, cross platform, GUI development tool.
- Responsive event handling and reliable

- Relatively fast development and libraries compatible with Python

OpenCV was selected for these reasons:

- Widely considered the de-facto vision library
- Cross platform with exceptional Python bindings
- Fast computation and development

The Arduino IDE and Bootloader are also used, for the following reasons:

- The ATMEGA1280 microcontrollers are compatible with the Arduino Bootloader variant.
- Open Source Community for fast and easy software development

4.2 Micro-Controller Level Software

Most of the code written is straightforward and serves one of two functions: interface, or control. The primary control board has firmware which does the following:

Interface:

- Controls the output to the display.
- Takes user inputs from several mounted buttons.
- Communicates with the IMU and off-board sensors.
- Communicates with the computer.
- Reads various voltages and other parameters
- Communicates with the micro-sd card.

Control:

- Actuates servos and auxiliary equipment.
- Enables and disables high-power status LEDs.

The motor control board has firmware which does the following:

- Interfaces with the computer.
- Controls the output and direction of 6 motors.

4.3 Software Algorithm

This section constitutes most of the true competition-relevant software. Anything in this section is executed within the Python environment, using a hierarchy of in-house scripts and libraries. In short, the competition process can be summarized with the following pseudo-code:

1) Read a file that contains position and angle information about competition way-points. Some of these way-points are also competition elements, and they are marked in the file as such, with relevant additional information.
    - All information in the file is input by hand. That is: all information about each obstacle must be previously known to a fair accuracy.
    - For example: A “Path” contains information about its position in 3-D space, in addition to its length, girth, and angle at which it is mounted.
2) Using this file as a reference, sequentially go to each of the way-points listed:
    - “Load” this obstacle or way-point. Determine the heading, and depth difference, between the vehicle's current position and that of the obstacle.
    - Perform any vertical motions first, then set the vehicle to point to the correct heading.
    - Using a PD controller, ensure that the heading and depth stay on-course while traveling to the next point.
3) If the way-point is also an obstacle or competition element, then perform the relevant task.
    - For most obstacles, this task involves enabling the camera to update the current position, and/or execute a script that is specific to that element.

4) Repeat (2) and (3) until the competition run is complete.

How (2) and (3) are performed is discussed below.

4.3.1 Motion Details

Step (2) relies on knowing the current position of the vehicle, in addition to that of the waypoint. In order to know the vehicle's position, a Kalman-filter has been implemented. The Kalman-filter takes in information from the IMU, compass, cameras (when available), and hydrophones to best determine the estimate of the current state of the sub.

During normal operation, where good vision information is not available, no position updates from the camera are used. In operating conditions where the vehicle is near-enough to a visually identifiable object, such as a path or obstacle, the cameras are used to update the position estimate of the vehicle, with an assumed low variance. This is done by determining the relative position of the vehicle with respect to the obstacle, by inspection of the image, and then assuming that the position described in the file of step (1) is correct.

5. Competition Tasks

The team developed and tested the system incrementally over the course of a few months testing each competition task individually until the system could complete each task satisfactorily. After each task could be completed independently the team ran as much of the course as could be simulated in the University pool.

The team began by developing a method of detecting the various competition objects by using the onboard camera and a vision processing algorithm. Simulated gates and objects were created and tested. Using the onboard camera to detect the objects was accomplished by applying a threshold to the Hue, Saturation, and Value (HSV) planes of the image. This threshold only allows pixels that fit within an empirically determined range for each buoy color to pass the filter. Using this threshold produces a binary image. Pixels that do not fit within the HSV range are zeros, and pixels that match the filter are labeled as ones.

A similar vision approach of empirically deriving a set of threshold values was done for each colored competition object. Thresholds were found for each of the four colors of duct tape that will be in competition.

Table 1: Threshold Values for Vision Processing

	Orange	Green	Red	Blue
Hue	0-25	75-125	230-255	140-175
Saturation	150-215	200-255	160-220	230-255
Value	150-200	110-175	60-100	100-150

These thresholds were thoroughly tested throughout the year. Shown in Figure 12 is an original picture taken from the onboard camera and the image after being processed by the threshold software. The gate is very distinct and the system sets a drive point in the center of the two vertical posts to allow the system to drive through.

The team also tested the vision software in different lighting conditions to ensure that the system was capable of operating throughout the day regardless of the ambient light or shadows. Overall, the system achieved a success rate of 94% for detecting the orange and green objects, a 90% success rate for the red objects and an 85% success rate for the blue objects.

easily distinguish between the blue target and the background when the system is close to the object. When the system is farther away, more false positives are detected. Using the navigation and waypoint algorithms described above, the system will be able to get close enough to the object before turning on the vision algorithm, thus increasing the likelihood of detecting the target.

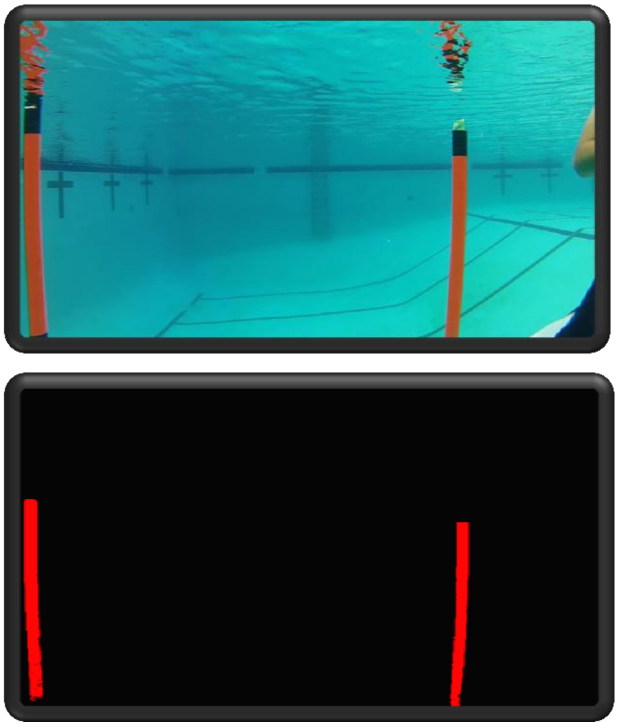

Figure 12: Original and Processed Gate Images

For the Buoy Training task the team used the same thresholds that were developed by the Embry-Riddle RoboBoat team. The RoboBoat team was very successful at detecting the orange, green and yellow buoys during the competition in June. Thresholds from the boat team were tested underwater from the subs perspective and slightly tuned for different lighting conditions. The correct sequence of colors to strike during this phase of competition can be programmed into the system using the user interface described above.

The blue and red targets for the “Et Tu Brute?” task were more difficult to see. The red was easily distinguishable; however, the blue blends in with the background and a large number of false positives were detected. However, through testing and tuning the thresholds, the false positive detection rate was significantly decreased. Example images of the “Et Tu Brute?” task are shown in Figure 13. The system can

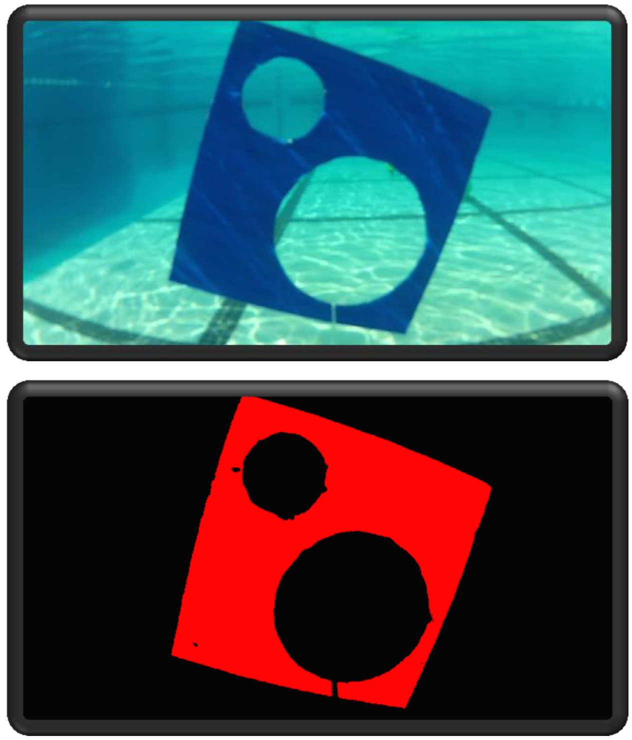

Figure 13: Original and Processed "Et Tu Brute?" Images

For the Gladiator Ring task the vision algorithm described above is not very successful. Black and white objects are much more difficult to distinguish than the other vibrant colors. So another algorithm was developed using a HARR algorithm. HARR algorithms are typically used in face detection software. By sampling many test images with each of the bins the algorithm will be able to learn the pattern in the bottom of the bin and attempt to find matches during this phase of competition.

The simulated bins created by the team are not exact replicas of the competition objects, so more data will be collected during the practice days of competition.

6. Remote Debugging

For development and testing, an Ethernet tether can be plugged into the vehicle to communicate with the computer using a Windows Remote application. The vehicle can be remotely operated with a joystick, and all variables and sensor values can be inspected and modified through the GUI. In addition, the main control program can be remotely modified. All of this is possible while the submarine is submerged and operational.

7. Conclusion

BlackFinn is a fully autonomous underwater vehicle designed and manufactured by engineering students at Embry-Riddle Aeronautical University. In developing BlackFinn, the team maintained a mission focus, seeking to meet or exceed the competition expectations. Additionally, we wanted to create a platform that could be used in further research, not just devoted to this competition. We believe that BlackFinn demonstrates exceptional systems integration, combining proven software and hardware solutions with unique ideas and novel solutions to accomplish the mission tasks.

8. Acknowledgments

Team Blackfinn would like to thank Embry-Riddle Aeronautical University and the Robotics Association at Embry-Riddle for their support during the design and implementation of the Blackfinn vehicle, Sparton Electronics, Seabotix, and GoPro for their generous donations to the team, and our advisers, Dr. Charles Reinholtz and Dr. Tim Wilson, for their support, encouragement, and advice.