Florida Atlantic University's Vision-Based Autonomous Surface Ship: Design and Implementation of the Second Generation V-BASS

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Figure 1: **The acclaimed V-BASS: Vision-Based Autonomous Surface Ship platform.**

Abstract- **Florida Atlantic University's Marine Robotics Team has implemented a rapid overhaul of their last generation Vision-Based Autonomous Surface Ship, acclaimed V-BASS, as was introduced as a prototype to their fleet of unmanned surface vehicles for last year's AUVSI and ONR sponsored 5th International Roboboat Competition. V-BASS's modular design has allowed this year's system to evolve to become faster, smarter, and far more reliable. The vehicle has adaptive control capabilities using computer vision, layered software architecture for platform control, a high-level state scheduler for mission management, and an interactive simulator for mission planning.**

I. Introduction

Autonomous Surface Vehicles (ASVs) guided solely by waypoint navigation are limited in their ability to operate in constantly changing environments, such as ports and harbors, where the positions of obstacles may be entirely unpredicted or where GPS coordinates may be difficult to acquire, such as under bridges. FAU's second generation V-BASS is a vision-based control system that can be used to exploit real-time computer imaging information, rather than depend on pre-determined routes.

Adaptive surface vessels are still of a new breed of unmanned vehicles, however, reliable designs are currently at a competitive race, both in the industry and in research. The AUVSI and ONR International Roboboat competition is designed to challenge highly motivated collegiate students that can rise to the occasion to come together as a team to rapidly develop such a system. This style of exercise provides the student a real-world simulation of being delivered a distinct set of mission requirements and an allotted time to complete such tasks. These tasks include, the ability to show vehicle propulsion strength and speed, with the agility to navigate through a buoy field, locate and engage correct objects of interest, shoot foam missiles at specified targets, provide multi-vehicle collaboration with an on-board auxiliary vehicle, and visually track, home towards, and recover a moving object of importance without any human control or interaction.

Florida Atlantic University has a plethora of experience in developing systems for the maritime industry. Maintaining such prestige has brought this year's team to formulate a multi-disciplinary group that includes students from the Ocean and Mechanical, Computer Eng. and Computer Science, and Electrical Engineering departments. Such compartmentalized expertise allowed focus to be placed on solidifying V-BASS at the platform level, allowing for the most accurate and robust set of tools (both mechanical and digital) to be utilized by the high-level system software.

II. Design Overview

The second generation FAU Vision-Based Autonomous Surface Ship utilizes computer vision (CV), a digital compass, and GPS to navigate. Propulsion is accomplished by brushed DC motors attached to a catamaran hull, while maneuvering is achieved using differential thrust. Electrical power is provided by lithium polymer (Li-Po) batteries, and autonomous commands are executed via a single board computer. The vessel is outfitted with many auxiliary systems including a Nerf missile launcher, an IR thermal sensor, and even an auxiliary vehicle. Other features include a Wi-Fi and RF modem communication for safe, manual operation.

III. Hulls and Superstructure

The key factors in determining the hull for V-BASS were stability, cost, and time. The hull team explored many options and a trade study determined that the optimum hull for the V-BASS is a catamaran. The catamaran platform provides transverse stability due to the dual hulls and wide beam, and the availability of a pre-built hull of this type made this option very cost effective. The V-BASS team re-purposed a catamaran hull from a retired FAU unmanned surface vehicle named "Nereus". The hull was modified to meet the AUVSI Roboboat Competition size requirements.

For this year's competition, VBASS has had a new paint job to "Ferrari Red", and has an enhanced superstructure to equip the newly required payload, while still satisfying the competition height requirements.

IV. Propulsion System

The vehicle utilizes differential thrust for turning, providing maximum maneuverability. The first generation propulsion system was accomplished by two shrouded propellers connected by straight shaft to two in-board DC brushed motors. The motors directly connect to the propeller shafts via custom couplings. The shafts traveled through stern tubes/stuffing boxes and out through the transom. This caused leaks and was difficult to maintain the motor, its mounts, and its couplings.

Figure 2: V-BASS hull getting prepped for mounting new Seabotix thruster mounts.

The second generation V-BASS has been stripped of the old propulsion system and enriched with two state-of-the-art Seabotix outboard thrusters, which provide far more robustness and power. The thrusters required specialized motor mounts to be design and fabricated.

Figure 3: **New Seabotix thrusters mounted.**

V. Electronic System

The electrical system on V-BASS provides robust, independent, and modular control to each subsystem component. The core of the vehicle's system is a TS-7800 single board computer with ARM9 architecture. The TS-7800 is mounted to a motherboard that was designed in-house, allowing all of the needed sensors and motors to be interfaced as desired.

The TS-7800 Motherboard contains many on-card devices, in particular: the R/C Master/Slave Control Switch (toggles autonomous mode into manual mode), the Pololu Maestro Mini (generates PWM signals for the motors), power monitoring and regulating systems (including three analog buffers), connection for the digital compass, on-board status LEDs, two water leak detection sensors, house-keeping inputs for R/C and RF activity, and a watchdog timer for mission time-out.

Last year's vehicle prevented many opportunities to shine when the vehicle ended up "dead in the water" because of connector failures or heat issues. The second generation V-BASS is equipped with industrial-grade IP67 waterproof connectors, providing far more durability than the previous design.

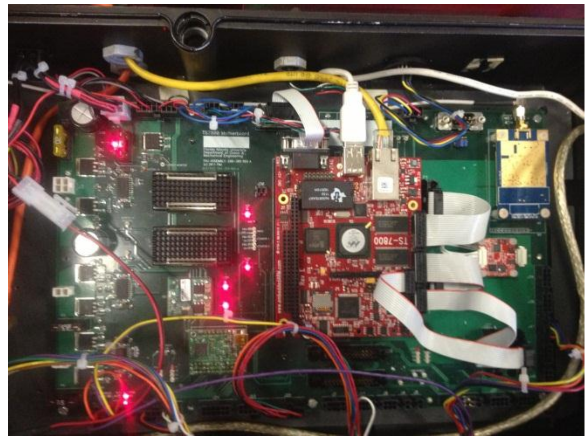


Figure 4: **V-BASS's state-of-the-art computer system.**

Heat issues were eliminated by adding PC fans strategically placed inside the electronics box. One fan is designed to circulate the warm air around a baffle attached to the box's lid. As the circulation approaches the rear end of the box, an exhaust fan is used to expel the warm air.

VI. Layered Software Architecture

The TS-7800 uses a Linux Kernel 2.6 with full DEBIAN distribution operating system. The system's layered design essentially provides independent and parallel control for each subcomponent on the platform.

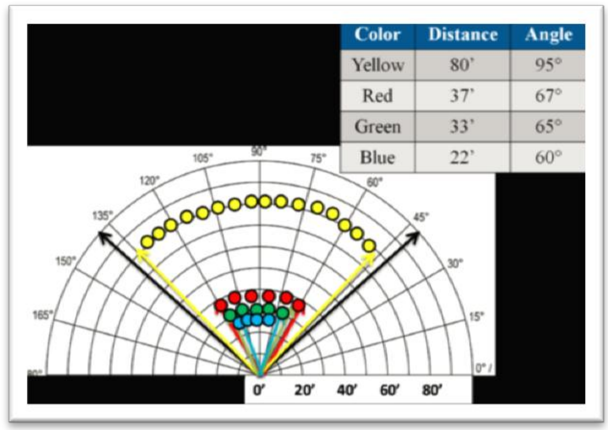
Using a systematic design approach, the second generation V-BASS has been equipped with a preemptive high-level mission scheduler that controls the V-BASS platform during a mission. This manages different priority—based attempts to accomplish the mission as a set of objectives that contains defined tasks, in which are carried out by organized processes or “threads”. Several programs are independently run to manage these processes, and are linked together using the Lightweight Communication and Marshaling (LCM) interface.

High-level commands are simply used to work with middle-layer programs that control general vehicle components such as navigation, data filtering, data logging, house-keeping functions, and communication. The middle-layer software is also used as control-ware, or threads used to work with devices drivers to interface with motors and sensors at the device level.

VII. Vision System

The vision system is comprised of a Point Grey Bumblebee2 stereovision camera for image recognition and target ranging. It is also packaged with a Fit- PC2 computer dedicated for image processing. Software from OpenCV is used to threshold colors of interest, and determine blob location and size. Feature detection is performed by utilizing a sophisticated image processing algorithm known as “SURF”. The vision system software outputs data to the control board via LCM in order to direct the vessel, as needed.

Stereoscopic computer vision allows the overlay of two rectified images provided by separate cameras with an accurately defined baseline between them. The processed output is a disparity image, in which provides a heat map of approximate distances to detected objects. This information is used to calculated an approximate range and bearing to various targets.



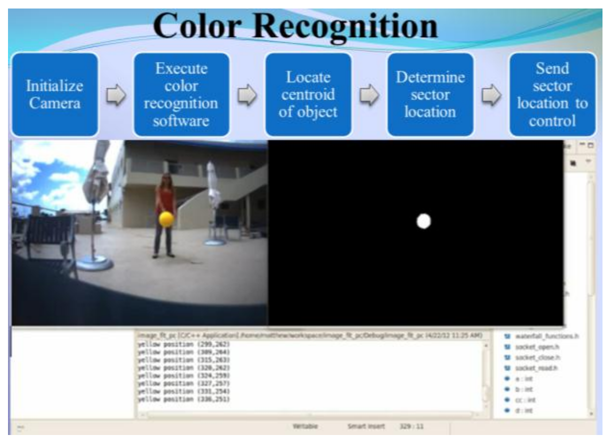


Figure 5: Color tracking calibration using OpenCV for image thresholding.

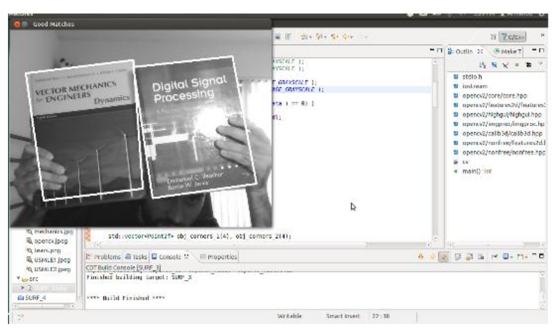


Figure 6: Feature detection using the SURF algorithm.

VIII. Mission Command Structure

Adapting the outline of a command and control structure found on naval ships aided in the design of V-BASS command structure. To connect these concepts to the system design, a separate nomenclature was used to identify each system's responsibilities while maintaining the typical layered command and control structure.

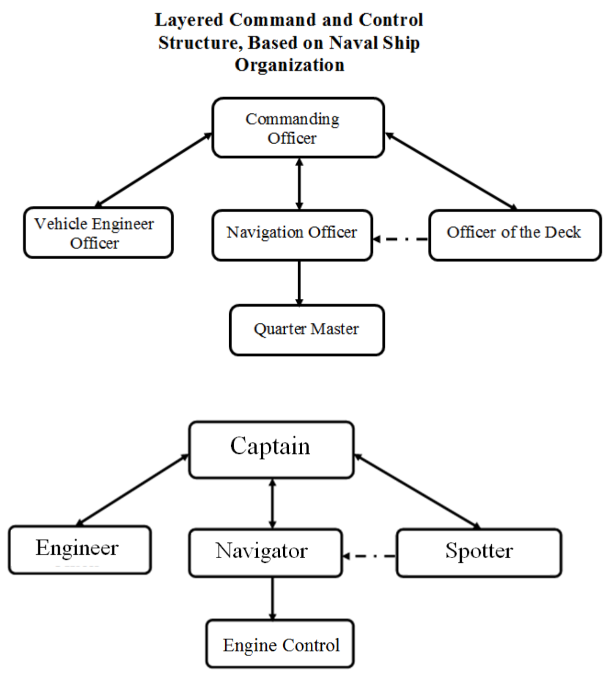


Figure 7: V-BASS Mission Command and Control Structure adapted from Naval Ship Command and Control structure.

Captain:

The responsibility of the Captain is to intercept messages from the Spotter and the Engineer and compare the messages against its mission plan to ensure that the vehicle is able to perform the necessary task at hand. Once the Captain makes a decision, it provides a desired heading and speed to the Navigator. If the Captain receives a message from the Engineer that a component on the vehicle is not in working order, then it will transmit a message to shore base to alert the user via RF modem.

Spotter:

The responsibility of the Spotter is to process the camera information to determine an estimated desired heading based on location of the buoys. The spotter will also determine whether if an obstacle avoidance routine needs to be performed and is responsible for carrying out such positioning. The spotter's deliverable is to provide a desired body-fixed heading and speed to the Captain via LCM based on what objective and task is at hand.

Navigator:

Once a desired heading and transit speed has been determined, the Navigator is responsible for converting the desired body-fixed heading into a geographical heading (North, East, Down frame of reference). The Navigator is also responsible to receiving a desired GPS location from the Captain. The Navigator shall then determine the vehicle's current GPS position and calculate a desired path plan in order to get to the desired GPS location. Once a desired geographical heading and transit speed has been packaged, the Navigator updates this information to LCM for the low-level control code to utilize.

Engineer:

The Engineer is responsible for checking for system failures that have occurred on the vehicle, determine if they can be fixed, and report this information to the Captain. In particular, the Engineer will check the leak detect probes, battery power, control box temperature, and determine that the thrusters are still working so the vehicle is not incoherently dead in the water during a mission.

IX. Navigation System

Navigation throughout the mission is controlled using the platform's state-machine. Throughout the mission, navigation modes change as to satisfy the required objective at hand, or a particular task within an objective. In such case, the vehicle may choose to use GPS waypoint and compass heading control, or it may choose (most commonly) to use the vision system as the primary navigation source.

Waypoint Navigation:

For this year's competition, the judges have provided a list of GPS locations in which each challenge station can be approximately found. This information is provided to the vehicle using a lookup table that is programmed in a high-level mission configuration file. Upon programming, each location is provided a default geographical heading in which the vehicle shall station keep towards before it starts the search pattern for the given objective.

The GPS waypoints are utilized to transit the vehicle from one objective to another once a previous objective has been completed or in the case that the attempt to complete the objective has failed or timed out. During such scenario, the desired source of navigation is directly computed by the "Navigator" using the lookup table. The "Spotter" then provides real-time processed vision information in the case the vehicle needs to be interrupted to perform obstacle avoidance during the transit.

Vision Navigation:

The vision navigation process is performed using two separately running functions: the "Spotter" and the "Navigator". The vision system (FitPC2 and Bumblebee2 camera) is a self-contained package in which provides an output, much like a sensor, of the range and body-fixed bearing to objects of interest as requested by the "Spotter".

The "Spotter" uses this information to determine a desired direction that the vehicle should maintain in order to get to the location to perform its next task. This navigation process is performed as an independently running control loop provided a particular objective and task number from the state-machine. The overall output from the primary navigation process ("the Spotter") is a desired body-fixed heading which is published to a specified channel on LCM. This message is then received by the "Captain", in which whom calls a function ("the Navigator") that transforms the body-fixed heading, into a geographical heading. This function will also filter the received heading values from LCM, as to smooth the vehicle response.

X. Challenge Stations

Each challenge station is tackled as a separate objective within the overall mission, leaving eight objectives in total. Each objective is given an allotted amount of time to be completed by the vehicle based upon objective priority and approximate known time to complete the list of tasks. A watchdog timer with a lookup table is used to keep track of the allotted time for each objective to be completed.

Speed Gate Navigation:

In order to navigate through the speed gate, it was felt that it would be most efficient to navigate using dead-reckoning; while active vision navigation may hinder the vehicle's speed due to attempting to correct the vehicle pose.

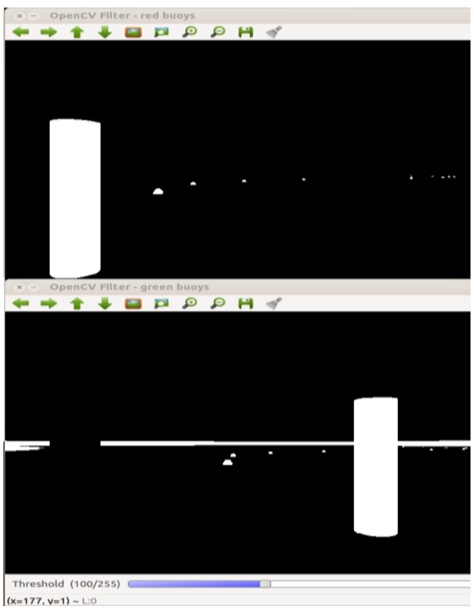


Figure 8: Threshold image of vehicle approaching end of speed gate.

The idea behind the speed gate is to provide the straightest track line possible while maintaining the most possible constant speed to both thrusters. The well hydro-dynamically shaped hulls for V-BASS provide optimum directional stability, especially when operating within the upper limit of its designed speed regime. Such stability provides trust that the vehicle will stay on track.

Navigate the Buoy Channel:

To navigate the buoy field, V-BASS primarily relies on vision navigation. This is accomplished by having the "Spotter" to use the vision system to determine the approximate range and bearing to the closest red and green buoys. Using the bearing to each buoy, the "Spotter" calculates a bisecting angle, or a resultant body-fixed bearing in which points directly between each buoy set it acquires.

The resultant bearing is then used as the body-fixed desired heading for vehicle navigation.

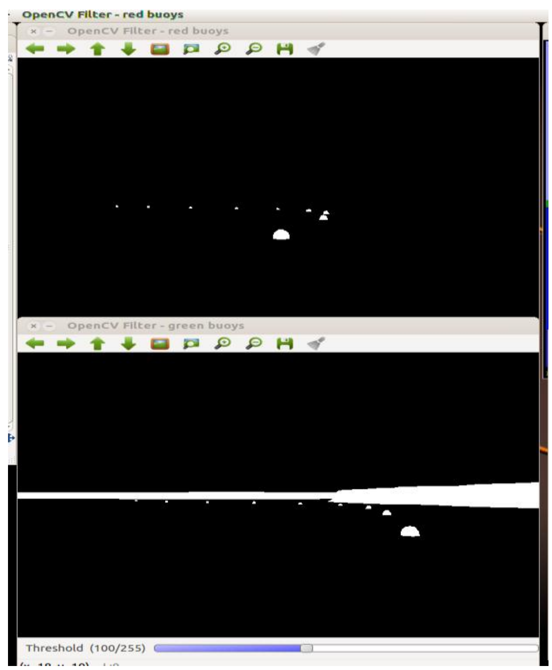


Figure 9: Threshold image of vehicle entering into buoy channel.

Sneaky Sprinkler:

The Sneaky Sprinkler station is the first of the waypoint stations that the vehicle will attempt. Once at the desired waypoint the vehicle will turn such that it points towards a default heading for this objective. The "Spotter" will then locate the station using a search pattern for the describe shape and color of the button pattern using SURF. The vehicle then utilizes the body-fixed bearing to the detected button as the desired heading. As the vehicle gets closer to the button, it looks for a white buoy just below the surface. The detected button associated to the same bearing as the detected white buoy is then the chosen button to ram with a button depressor located on the forward section of the hull.

Shoot Through the Hoops:

This challenge is tackled by transiting the vehicle its default GPS location and heading for this objective. Using the vision system to color threshold for the desired rings, the "Spotter" provides the vehicle with a desired bearing towards the ring with the best estimated position. It is expected that the most difficult part of this objective is detecting the rings themselves, dependent upon how thin they are.

Figure 10: Nerf Missile Launcher.

An auxiliary Nerf missile launcher has been installed on the new second generation V-BASS. The mounting assembly was angled and mounted to provide the most consistent trajectory that the gun seemed to operate at.

Using a thoroughly tested calibration, a lookup table is used to provide V-BASS with a standoff distance from the hoops in order to provide the correct position for the ideal trajectory.

Catch the Ball

Catch the ball is one of the competitions favorite objectives. This year will be the first time that FAU plans to attempt this objective. Like all of the other objectives, V-BASS will first transit to a default location and will be provided a default general heading. The "Spotter then utilizes color tracking to identify the purple tape strips around the edges of the dock. Using the body-fixed bearing of the dock, the vehicle can align itself and slowly home in. As it approaches the dock, the SURF algorithm is used to create more accurate feature detection and thus better navigation estimation. Using a lightweight serial bus, the V-BASS main processor sends a trigger message to a low-cost Arduino based auxiliary system. The Arduino controls an automated launch and recovery device used to house the auxiliary vehicle. The launch and recovery system is a vertical door mounted on the forward portion of the vehicle and contains a high-torque servo used to rotate the door once attached to the dock. To attach to the dock, V-BASS simply drives into it and then provides an equal amount of thrust to each motor to stay attached. Once attached, the trigger signal is sent to the Arduino board to allow the door to open and launch the auxiliary vehicle. The auxiliary vehicle is a simple Lego Mindstorm programmed to perform a dead reckoned search pattern to locate the puck. Upon retrieval of the auxiliary vehicle, a small motor is turned to reel in a line attached to the auxiliary vehicle. A serial string is then sent back to the main CPU so the next objective can be started.

Rock, Paper, Scissor, Lizard, Spock :

For this objective, it is intended for V-BASS to use a combination of the previously discussed visual search techniques to locate and orientate the ship about objects of interest. For this task, the "Spotter" will first locate the cards using a combination of edge detection and SURF. At this point, it will only use this information to position the vehicle in front of the challenge station. The vehicle then uses the onboard IR temperature sensor to detect the warmest card. Once detected, SURF is then used again to identify which card is the warmest.

Depending on the detected card, a lookup table is used to decide the playing move that will be reported back to shore base.

Capture the Flag:

This objective is the last of challenge stations to be attempted. For this task, the "Spotter" will simply use the vision systems color tracking capabilities to constantly provide a desired bearing to the blue flag. The vehicle is then in hope to get close enough to use v-shaped rubber grooves to frictionally grab the flag.

XI. Control System :

V-BASS primarily uses a heading and speed controller to maintain desired vehicle pose. Due to the differential steering, the vehicle heading controller differs from those that utilize rudder steering systems as in [1]. Differential steering imposes a moment about the vehicle that causes it to turn. There are distinct advantages to this type of system; primarily, the turning radius for the vehicle is substantially reduced, as well as the addition of the capability to steer without the requirement of a forward speed. With this configuration, the controller manages vehicle direction by two separate proportional control laws. Each of these controllers focuses on a single motor. Owing to the yaw North-East-Down (NED) convention, the port controller would have a positive slope, while the starboard controller would have a negative slope [2].

A forward speed is denoted by a percentage of full-scale motor power and is used to bias the proportional control law to the desired steady-state vehicle speed. This bias value is allowed to fluctuate to accommodate a speed controller, i.e., if the vehicle is moving to slowly, this value would increase until the vehicle reaches the desired steady-state speed. Much like the heading controller, the speed controller operates on a proportional control law, and thus, has a separate gain value. Due to the coupling effect of differential steering, the gains affecting the heading controller and the speed controller are interrelated and need to be tuned as a couple.

To better handle real world scenarios, a tolerance region is implemented where the error is less than five degrees, as well as a saturation value above 100% and below -100%. This is to account for heading disturbance errors caused by wind and wave forces. When within this tolerance region, both motors would have the same percentage and the same thrust, ideally causing the vehicle to follow a straight line. The figure below displays an example of the proportional control law for both motors with a positive thrust. The absolute value of the slope of the motor command corresponds to the proportional gain value for the heading controller [2].

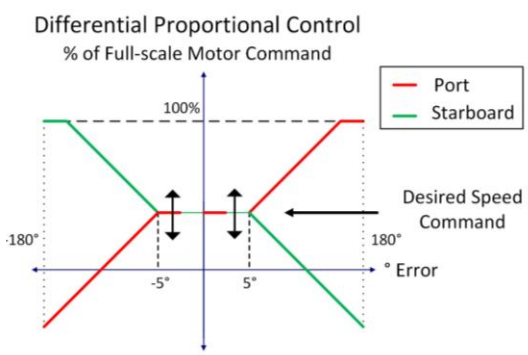


Figure 11: The acclaimed V-BASS: Vision-Based Autonomous Surface Ship platform.

XII. Mission Management

In order to help facilitate the launching of several parallel processes, and managing their resources, we have interfaced with using the Bot Procman package. This program is interface with our high-level code, and LCM-Logger to help debug programming issues.

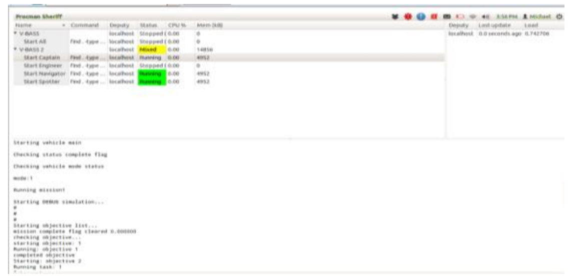


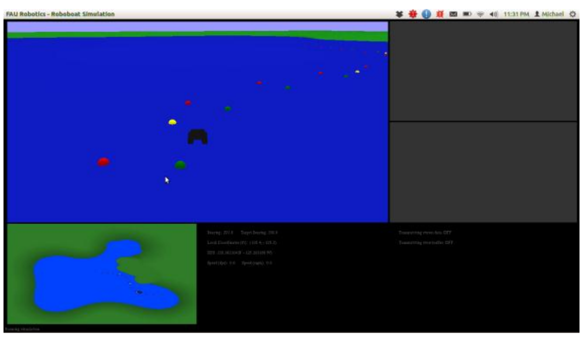
Figure 12: Bot-Procman used for process management.

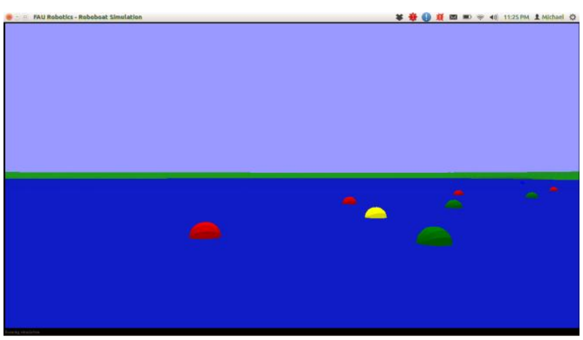
XIII. OpenGL Simulation

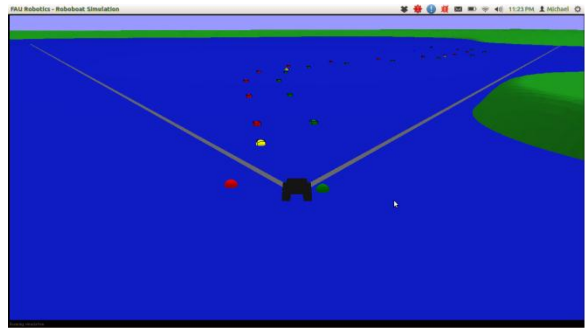
The motivation in creating a simulation was to allow us to test frequently and to modulate the development of high and low-level code. The simulation displays both the 3D visualization of the course, as well as continuously displays the values of common sensor values. Some of these variables include the boat's position, compass readings, speed, objects in view, etc. Much of the robots behavior was developed and simulated before actually integrating with the motors, computer vision, and sensors package.

The simulation is programmed in C++ in an object-oriented style. It is structured using a strong Model-View-Controller framework. The Model is the physical course, the View is the 3D representation of the Model using OpenGL, an open-source graphics language, and the Controller handles user input such as mouse and keyboard events. The controller also handles things like file input and output and basic messaging.

One of primary uses for the simulation was the buoy navigation challenge. Because navigating through a buoy channel with sharp turns and yellow buoys is error prone, being able to test the robots behavior with a variety of buoy tracks is a major asset to the second generation V-BASS. Hand placing every buoy in the track was also not desirable because it is difficult and time-consuming for the user, and would result in rough, or noisy looking tracks. Lastly it should be easy to make small adjustments to existing tracks. With the requirements of being highly expressive, easy to use, and finely tunable, Bezier Curves were chosen to generate the buoy tracks. They are manipulated using "control points". Moving a control point to the left, for instance, will stretch the curve to the left, resembling an elastic material. The simulator integrates with the high-level vehicle code using LCM.







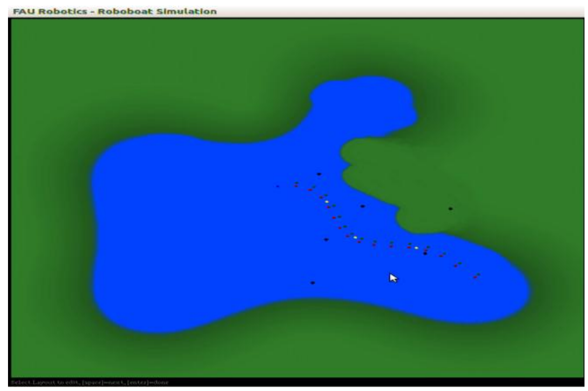


Figure 13: Screenshot images of the FAU Roboboat Simulator. The images show different views that can be used to help program vehicle intelligence. The aerial view of the simulator in the last image shows actual competition lake used in courtesy from Google Earth.

XIV. Conclusion

The Marine Robotic Team's goal this year was to remove all of the bugs that occurred during last year's competition. Although we were under budget, we used simple ingenuity to make the second generation V-BASS a world of a difference from the first generation V-BASS. Where there's a will, there is a way, and this year's team has gone above and beyond to prove what they're capable of in just a couple months to work at it. V-BASS is molding into a highly modular and robust system. The key is to keep this on track. Even the smartest high-level code can't perform well with an unreliable platform. This year's vehicle will be providing FAU with their most high performance competition system yet.

References:

[1] Fossen, T., 1994. Guidance and Control of Marine Vehicles, 1st ed., John Wiley & Sons Ltd, Baffins Lane, Chichester, West Sussex PO19 1UD, England.

[2] Bertaska, I. et al., 2013. "Experimental Evaluation of Approach Behavior for Autonomous Surface Vehicles". In Proc. *ASME Dynamic Systems and Control Conference,* 2013.