The FAU Vision-Based Autonomous Surface Ship: V-BASS

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Abstract: This paper describes the design and functional/performance testing of the FAU Vision Based Autonomous Surface Ship (V-BASS), which has been developed for the 2012 AUVSI RoboBoat Competition. The V-BASS utilizes a stereovision camera system to autonomously navigate, identify targets, and avoid obstacles in real time.

1. 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 continuously changing or where GPS coordinates may be difficult to acquire, such as under bridges. The V-BASS vessel uses a vision-based control system to take advantage of real-time vision information, rather than depending on pre-determined routes.

2. Detailed Design Description

The V-BASS utilizes stereovision, a 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 batteries and autonomous commands are executed via a single board computer. The vessel is outfitted with many auxiliary systems including a water cannon, thermal sensor, and button depression system. Other features include a Wi-Fi router for data transmission and radio communication equipment for manual operation. Figure 1 illustrates the vehicle's component configuration.

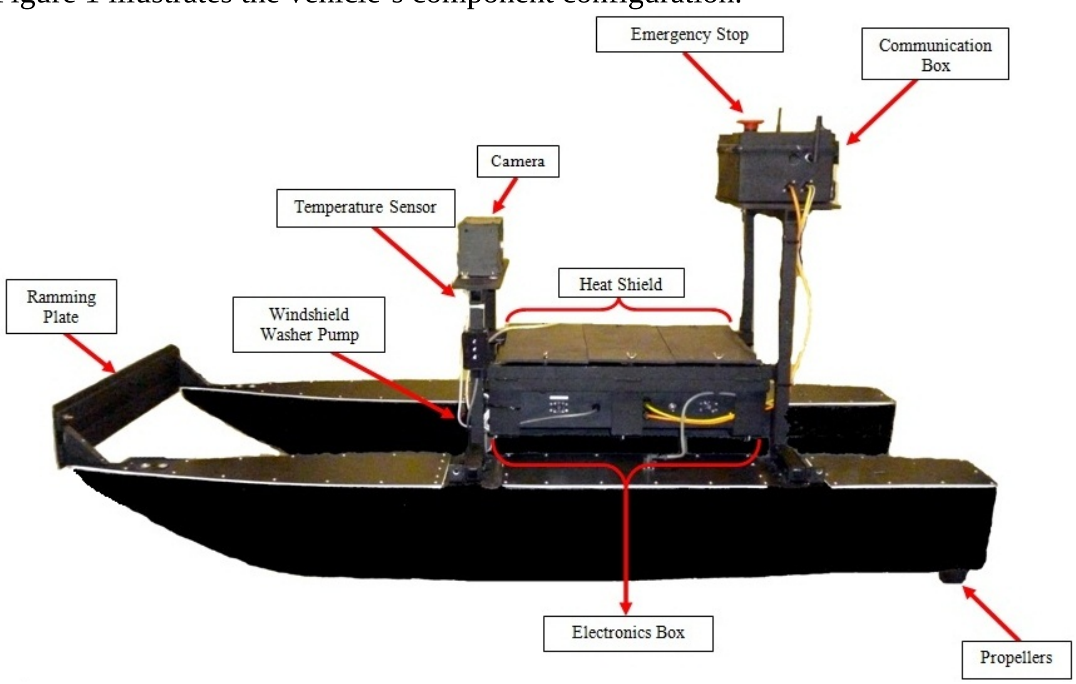


Figure 1: Component Configuration

Structural System: 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 an ASV called the Nereus. The hull was modified to meet the AUVSI Roboboat Competition size requirements.

Propulsion System: Propulsion is accomplished by two shrouded propellers connected by straight shaft to two DC brushed motors. The vehicle utilizes differential thrust for turning. The propulsors for the V-BASS include two bronze four-blade A-series (Ka 4-70) propellers shrouded in custom 19A Kort nozzles. Two Pololu motor controllers drive two Graupner 900 BB torque brushed DC motors respectively. The motors directly connect to the propeller shafts via custom couplings. The shafts travel through the stern tubes/stuffing boxes and out through the transom.

Power System: The V-BASS power system is designed to optimize the vehicle run-time while providing power efficiently to all components. Three identical 14.8V 5800mAh lithium polymer battery packs provide power to the vehicle; two packs for the propulsion system and one to power the electronics and auxiliary system. A custom-built motherboard (FAU TS-7800) distributes power to the auxiliary components through switching regulators and controller ports. The power distributed to the motor controllers is supplied through a protection circuit board. The system incorporates an emergency shutoff system which is actuated by a large diameter push button kill switch, or remotely via R/C signal. The kill switch is in a circuit with a 7 Amp solid-state relay switch across the water pump and two 100 Amp solid-state relay switches across the power supply boards. When actuated, the kill switch will shut off power to the propulsion motors and water pump while maintaining power to the main electronics board.

Emergency Cut-Off Switch: The kill switch is a 1 inch diameter button mounted on the top of the communications box. The kill switch connects to the electronics main board with 22 AWG wire via a bulkhead connector. The circuit travels across the board incorporating the RC kill switch. Also included in the circuit are the port and starboard power supply boards. The wiring travels from the motherboard through a bulkhead connector and into the mid hull compartment bulkhead connector of each side hull. Using 22 AWG wire from the bulkhead connector pin, connection is made to the control input of the 100 amp solid state relay. It then travels into the electronics box to the electronics board completing the circuit.

Vision System: The vision system is comprised of a Point Grey Bumblebee2 stereovision camera system for image recognition and target ranging, and a Fit- PC2 computer for image processing. Software from OpenCV was used to track colors and images. The vision system software outputs data to the control board in order to direct the vessel, as needed.

Table 1 : Vision System Components

Component	**Description**
Point Gray Bumblebee2	2.5mm focal length, 648x488 pixels, 97□ HFOV
Fit-PC2	1.6 GHz processor, 1 GB RAM (Random Access Memory)
Commel 1394a Firewire	Mini-PCI-e Firewire Adapter

Navigation System: The navigation system consists of a 3-axis digital compass, a GPS receiver, and the inputs from the vision system. The compass is utilized for dead reckoning when traveling through the speed gate and is used to follow a course from the end of the speed gate to the challenge station area. The GPS receiver is used for measuring the vehicle speed over ground as well as determining the vehicle's position when the vehicle is in the proximity of a target of interest. The primary input to the navigation system is data from the vision system.

Table 2: Navigation Components

Navigation System Component Specifications					
Part		*Power*	*Update Rate*	*Data Format*	*General Specifications:*
GPS	EM-408	0.25 W	1 Hz	RS232	Voltage: 3.3 V Current: 75 mA Accuracy: 16 ft
3-Axis Digital Compass	OceanServer 5000S	0.10 W	1 Hz	RS232	Voltage: 3.3 V Current: 30 mA Accuracy: 1º Resolution: 1º

Communication System: Bi-directional data communications are made via a Wi-Fi network and RF modem/receiver, and control signals can be received from an R/C transmitter via an R/C receiver (Table 3). The Wi-Fi network consists of a pair of wireless routers, one located on the shore base and one located in the communications box on the vehicle. The Wi-Fi network allows the vehicle to transmit real-time vehicle status information to the shore base during testing and is used for transmitting the GPS coordinates of targets of interest during autonomous missions. The RF modem has a longer range and is generally used for low level commands and updating the vehicle status. As the Wi-Fi system has greater bandwidth, it is generally relied upon for uploading executable code to the vehicle. The R/C system allows for manual control of the vehicle during testing phases, and incorporates a manual override function in case of an unexpected operating condition.

Table 3: Communication System Components

Communication System Component Specifications					
Part		*Frequency*	*Voltage*	*Current*	*General Specifications:*
Wireless WiFi Router	Linksys WRT54g	2.4 GHz	5 V	1 Amp	
R/C Transmitter	Futaba 6EXP	72 Hz	9.6 - 12 V	250 mA	6 channel system
R/C Receiver	Futaba R168DF	72 Hz	4.8 - 6 V	10 mA	Size: 2.20"x1.14"x0.79" Weight: 0.88 oz
RF Modem (2)	9XTend-PKG-U	900 MHz	7 - 28 V	110 mA	Range > 3000 ft.

Control System: The control system for V-BASS is a "layered control" architecture. Layered control essentially means that there are many layers that manage the vehicle's system in order to simplify the design complexity. It provides robust, independent, and modular control of each subsystem. The core of the vehicle's control system is a TS-7800 ARM9 architecture single board computer (SBC). The TS-7800 is mounted to a motherboard that was designed in-house.

The FAU TS-7800 Motherboard is essentially a breakout board that allows subsystem access to the necessary ports that are available on the TS-7800 SBC. The TS-7800 Motherboard also 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), power monitoring and regulating systems (including three analog buffers), a connector for the digital compass, on-board status LEDs, two water leak detection sensors, an H-Bridge circuit to control the water cannon, house-keeping inputs for R/C and RF activity, and a watchdog timer.

The TS-7800 uses a Linux Kernel 2.6 with full DEBIAN distribution operating system. The software for the V-BASS control system is written in C and utilizes system functions that were written from scratch to provide an application user interface, V-BOS, for mission planning. The layered design essentially provides an independent proportional controller for each subsystem that acts as a middleware application. At the device level, there exists a device driver, followed by the appropriate subsystem control-ware layer, the data storage layer, and high-level process layer that spawns the necessary system tasks. For this design, the control system utilizes a single-threaded approach, in which each process is polled independently and sequentially. The feedback for the vehicle's navigation system primarily consists of buoy color inputs from the vision system, speed over ground from the GPS, and the compass, which gives heading, pitch, and roll.

Auxiliary System: The auxiliary system consists of a water deployment system and a temperature sensor (Table 4). The water deployment system includes a windshield washer pump, located below the forward truss, attached to an adjustable bracket on the interior starboard hull partially submerged along with a water hose system to transport water from to a nozzle. The temperature sensor is mounted on the front arch of the vehicle, directly below the camera.

Table 4: Auxiliary System Components

Component	Description
ACI Windshield Washer Pump	Up to 4 gallons per hour
Phidgets IR Temperature Sensor	10° field of view, up to 380°C

3.0 Testing and Evaluation

Structural System: In order to meet the requirements, the entire system must weight no more than 140 pounds and fit within a size envelope of 6x3x3 feet. V-BASS was constructed to fit these criteria (Table 6). Another key factor that was taken into account was the buoyancy and tracking of the hulls. To maintain a stable system and provide the best setting for the camera, the V-BASS must track straight and have even buoyancy. In addition, a water-resistant container was needed to safely house the required electronic equipment. The electronics box chosen was tested to ensure a watertight seal. The heat generated within the box was carefully monitored as well to ensure it remained at a safe operating temperature for the equipment.

Table 5: Structural System Final Dimensions

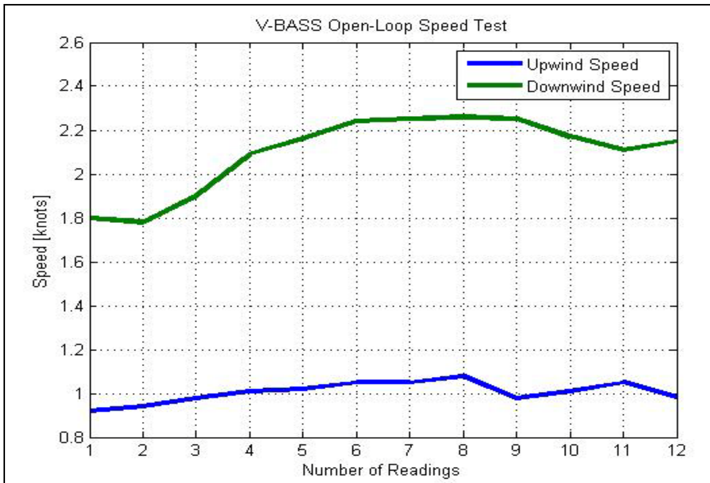
Specifications	Competition Requirements	V-BASS Dimensions
Length overall [LOA]	72 [in]	71 [in]
Beam overall [BOA]	36 [in]	33.25 [in]
Height	36 [in]	36 [in]
Overall Weight	140 [lbs]	90 [lbs]

Propulsion System: The calculated overall drag force of the vessel (with water and air resistance) is D_T= 2.70 [lbf]; therefore, the drag force per hull is D = 1.35 [lbf]. At constant speed, thrust is equal to the drag force (T = D). The diameter and pitch of the propeller was chosen as d = 2.8 [in] and P = 2.82 [in] respectively, giving an approximate pitch to diameter ratio of 1. The design speed of the vessel is U = 3 [kts] and the advance speed U_a = approximately 90% of U = 2.7 [knts]. The estimated propulsion powering is given in Table 7.

Table 6: Summary of Results for Propulsion System

V-BASS Propulsion System: Summary of Results for Design Speed of 3 knots			
Parameter	**Variable**	**Per Hull**	**Total Vessel**
Thrust	*T*	1.35 [lbf]	2.70 [lbf]
Thrust Horsepower	*THP*	0.01 [hp]	0.02 [hp]
Advance Ratio	J_a	0.59	
Propeller Shaft Speed	n_{prop}	37 [rps] = 2220 [rpm]	
Propeller Efficiency	η_{prop}	57%	
Maximum Motor Shaft Speed	n_{motor}	108 [rps] = 6500 [rpm]	
Motor Efficiency	η_{motor}	71%	
Delivered Horsepower	*DHP*	0.017 [hp]	0.035 [hp]
Brake Horsepower	*BHP*	0.019 [hp]	0.038 [hp]
Total Electric Horsepower	*HP(E)*	0.027 [hp]	0.054 [hp]
Torque at Propeller	Q_{prop}	0.47 [lbin]	

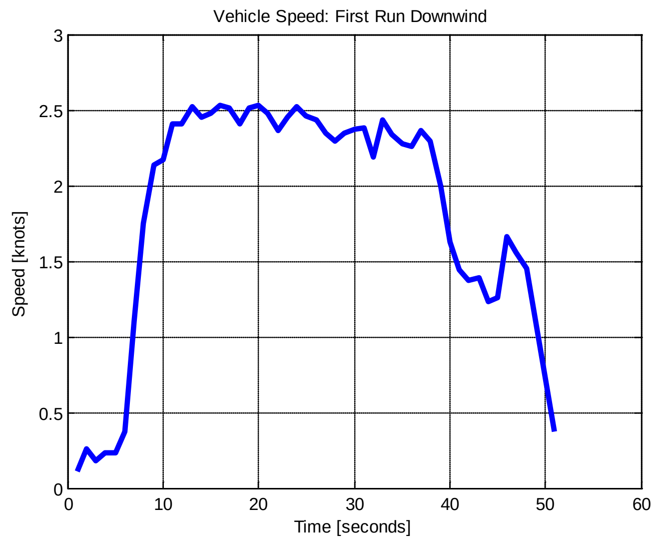
Propulsion System Functionality Test: This test was conducted to validate that the vehicle could maintain an average speed of at least one knot. Using R/C mode, the vehicle travelled an arbitrary distance in the downwind and upwind direction while acquiring ground speed updates from the GPS on board (Figure 2).



Downwind Average Speed [knots]	**Upwind Average Speed [knots]**
2.10	1.01
1.55 *Overall Average Speed [knots]*	

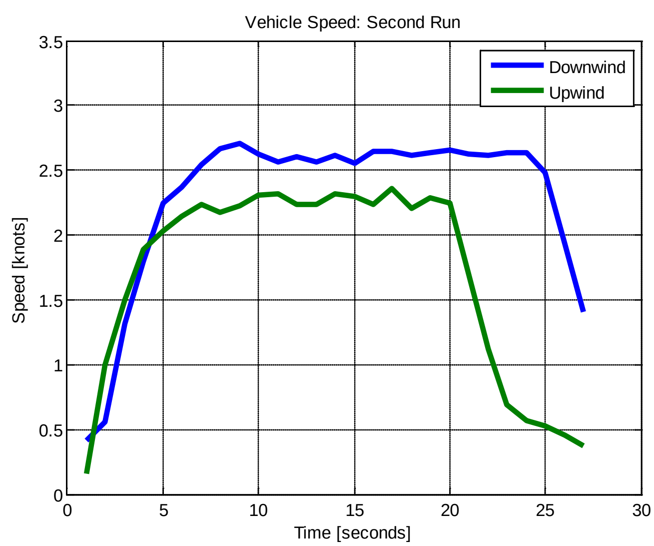
Figure 2: V-BASS Open-Loop Speed Test

Propulsion System Performance Test: This test was conducted to characterize the speed for a given duty cycle. Applying a motor command of 34 (~73% duty cycle) to the portside and 36 (~72% duty cycle) to the starboard side, the vehicle travelled an arbitrary distance in the downwind and upwind direction while acquiring ground speed updates from the GPS on board – the USV maintained a peak average speed of 2.38 knots (Figure 3-Figure 4).



FIRST RUN
Downwind Peak Average Speed [knots]
2.35

Figure 3: Vehicle Speed First Run Downwind



SECOND RUN	
Downwind Peak Average Speed [knots]	**Upwind Peak Average Speed [knots]**
2.58	2.24
2.41 ***Peak Average Speed [knots]***	

Figure 4: Vehicle Speed Second Run

<u>Power System</u>: The power system was developed by creating a power budget for the V-BASS. The budget is a list of the systems components and each component's power usage calculated from the current and voltage requirements. This budget estimated the amount of power necessary to operate the vehicle. The power was modeled over a time representation of the course using a

MATLAB code. Using the model, the total power supply needs for the propulsion, electronics, and auxiliary systems were calculated. Research was done into different power supplies, power regulation, and power efficiencies to determine the use of one 14.8V 5.8Ah lithium polymer battery to supply the electronics board and one 14.8V 5.8Ah lithium polymer battery to each propulsion system. The lithium batteries required a low-voltage and current discharge protection circuit board (PCB) to prevent them from becoming unstable. These PCBs were wired to each power system to prevent the need for each battery having its own PCB. Upon completion of the assembly of the system, the individual components were tested against manufacturer specifications.

The vehicle could not be tested for overall performance during a complete course run. However, the vehicle was placed in simulated states to represent the power usage for different sections of the course. The voltage change over a representative time similar to a test run was measured and recorded as well as current draw. The resulting data was analyzed using a MATLAB code used to model a full test run of the course. These results were compared to the initial model created from the battery budget. The actual battery usage was higher than the estimated values from the model. This is attributed to removal of the reduction gearing, DC to DC converter efficiency, and error from manufacturer specs coupled with measurement tools (Figure 5).

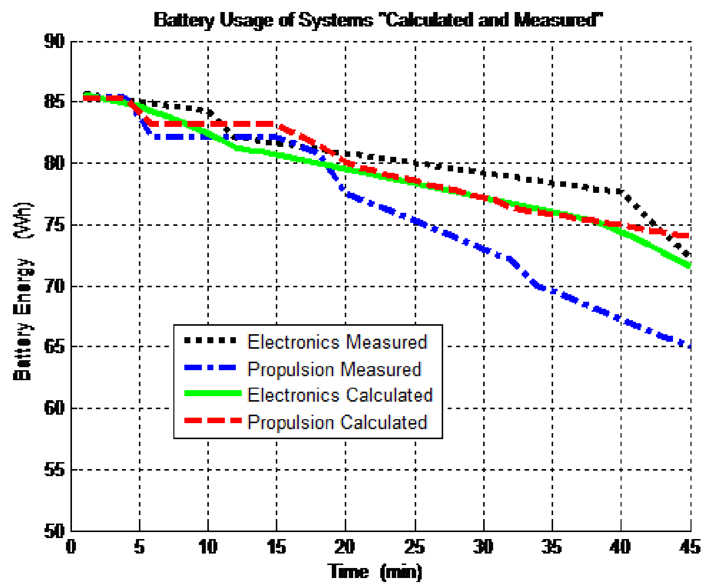


Figure 5: Calculated and measured system power consumption.

All lithium polymer batteries were tested using a set amperage draw from a load box in the FAU SeaTech Electronics Laboratory and performed the expected discharge rating given by the manufacturer and at a similar rate to a standard lithium polymer battery. The protection circuit boards were tested for a burst current discharge cutoff using an adjustable load box. The PCBs were connected to load box and current draw was increased in increments of 10 mA until PCB entered open circuit condition. PCBs open circuited at 8000 mA draw from load box. PCBs were tested for individual cell low-voltage monitoring. PCBs were connected to four 1000 ohm resistors in series with a power supply providing 14.8 Volts across all of them. A resistance box was used to increase the resistance across one resistor at a time simulating a low-voltage condition. The PCBs performed according to manufactures specifications. The solid state relays were also tested for control line response to voltage drop. A single pole switch was connected across the input power to the relay to the control line of the relay providing the necessary current to the control line for the relay switch to be active closed creating a circuit.

Auxiliary System: To complete the fire challenge, a bilge pump was initially selected based on pump head calculations, however the manufacturing specifications were not correct and the bilge pump would not suffice to meet the vehicle requirements. An automotive windshield washer pump was purchased and used as a replacement. This pump was purchased at a local automotive store and performance specifications were not available and prediction calculations were not performed. The windshield washer pump was tested for effectiveness and exceeded the requirements for projected distance. In order to complete the air challenge calculations were performed to determine the effective distance of the IR temperature sensor.

Vision System: Calculations where performed to quantify the accuracy of the stereovision, the maximum distance the camera can see, and the optimum height of the camera above the waterline. The summary can be seen below.

Table 7: Summary of Vision System Calculations

Test	**Result**
Max distance of a pixel:	1594.5 inches
Error of stereo vision at 39.37 inches (1m):	0.1935 inches
Optimum height of camera:	24 inches

Object recognition test: This test was completed to verify the robustness of the image recognition program and the maximum distance the images could be correctly identified. Placing images from the 2011 Roboboat competition on a window and using the image software with the camera at increasing distances, the software was run. The boat on fire was found at a max distance of 13 feet, the fire symbol at 10’, the water symbol of 10’, the wind at 5 feet, and the leaf at 5 feet.

Color Recognition test: This test was completed to verify the robustness of the color recognition program and the maximum distance colors could be correctly identified. The test was conducted by placing colored buoys in front of the camera at varying distances. The color recognition software was used to determine the max distance each color was seen by the camera. On a cloudless sunny day, the red color could be seen at a distance of 30 feet, green at a distance of 15 feet, yellow a distance of 21 feet, and blue at a distance of 15 feet (Figure 6). On an overcast cloudy day, the red color could be seen at a distance of 18 feet, green at a distance of 8 feet, yellow a distance of 10 feet and blue at a distance of 7 feet.

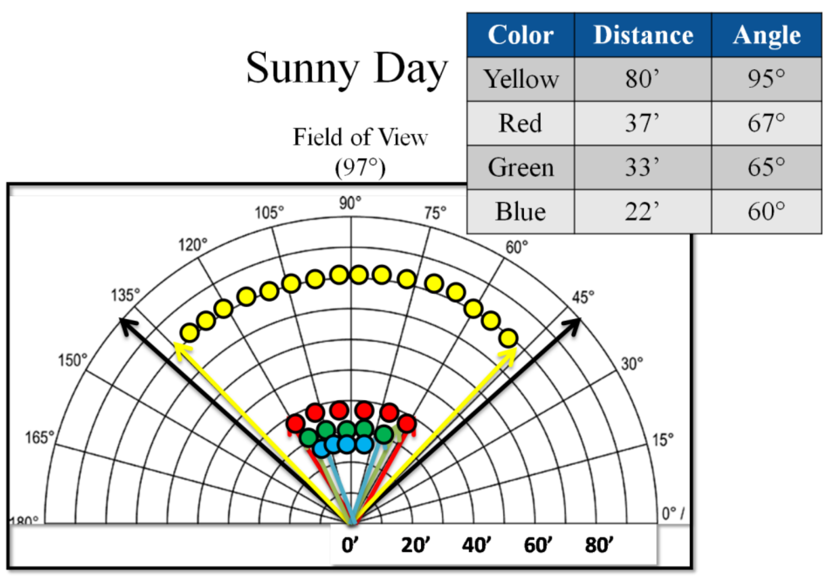


Figure 6: Performance testing of color recognition.

Fit-PC2: This test was completed in order to verify that required drivers were properly installed onto the vision processor. The camera was connected to the computer via Firewire cable. A sample program provided by Point Gray was run in order to test the functionality and communication between the camera and the Fit-PC.

Navigation System: Compass: The compass was functionally tested by utilizing it to maintain a course through the speed gate. A heading controller was written and in conjunction with the vision system, the vehicle aligned itself between the entrance markers of the speed gate and surged forward along the compass value read at the entrance to the speed gate.

GPS: The GPS was functionally tested by transmitting position data to a shore base computer via Wi-Fi network and comparing the data to points on GoogleMaps. The GPS was also utilized for logging speed over ground data for categorizing the propulsion system.

Communication System: R/C testing: R/C communications were established between the vehicle and the Futaba transmitter while the vehicle was on the dock. Both motors were actuated in both forward and reverse and the kill switch was verified to be functioning properly. The vehicle was then placed into the marina and driven North away from the dock with the supervision of a team member in a chase kayak. Another team member was following the progress of the vehicle on foot along the seawall. When R/C communications were lost, the team member on shore marked the location and measured the distance between the transmitter and the point of lost contact with the vehicle. This distance was found to be 280 feet. The requirement for range of R/C communications is 250 feet; therefore the vehicle passed this test.

Wi-Fi testing: Wi-Fi communications were established between the vehicle and the shore base computer while the vehicle was on the dock. GPS data was continuously transmitted to the shore base computer from the vehicle to ensure connectivity. The vehicle was then placed into the marina and towed north away from the dock by a team member in a kayak. The incoming data was monitored for loss of signal. When the vehicle was 850 feet away from the shore base and the Wi-Fi connection was still in place, the test was deemed a success as this distance is well beyond the max operating distance of the vehicle from shore base.

Control System: Test and evaluation for the vehicle's control system consisted of data logging vehicle attitude over a course track. The vehicle uses a close-loop heading controller which is expected to maintain a particular heading over a particular distance. The vehicle's dynamic response was data logged and plotted. The test was performed to validate that the vehicle has the ability to track a heading for a given amount of time. The pitch and roll response data was also collected to cross-reference against the heading response. The test was performed for two speeds: the vehicle's high speed

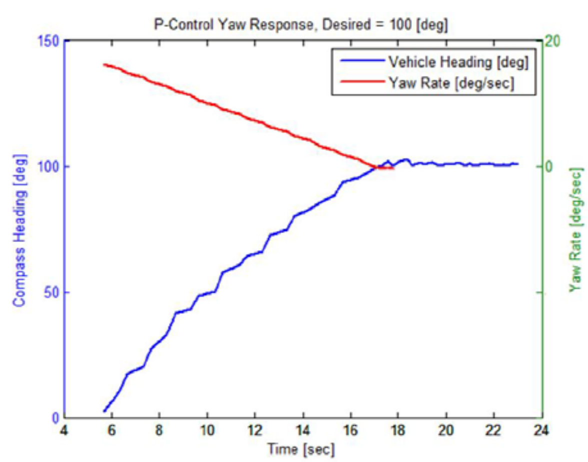


Figure 7: Closed-loop Heading Control.

mode used in the speed gate section and a slow tracking speed used for vision navigation.

Test Results: The vehicle passed the closed-loop heading test, as it proved the ability to maintain a given desired heading for a 1 minute time period (Figure 7). The results showed, however, that the heading track was more stable in high speed than in vision tracking mode. The vehicle's pitch and roll response were also more stable at high speeds.

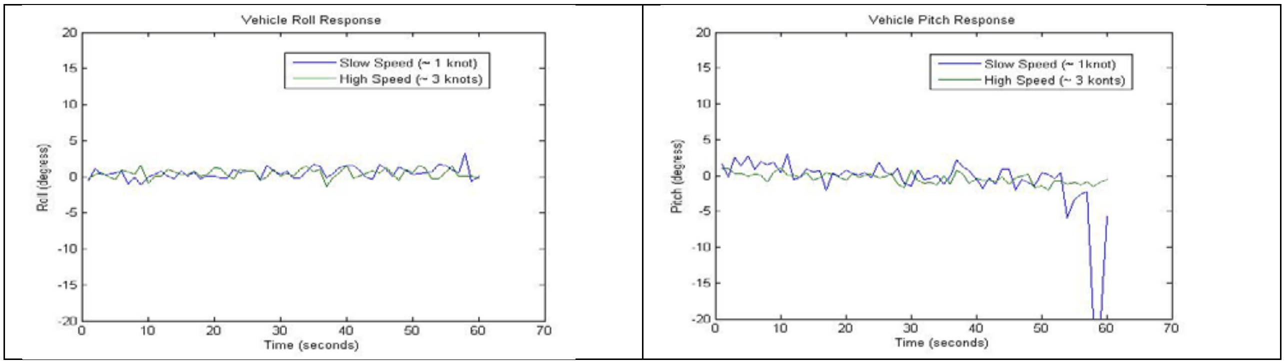


Figure 8: Vehicle Roll and Pitch Response.

<u>Systems Integration Testing</u>: To begin the integration process, remote control of the vehicle using the R/C system was established. Following successful remote control, an open loop time based controller was developed and implemented. This controller commanded the vehicle to travel autonomously for a designated time and then stop. The compass was then integrated, by developing a heading controller. Using this controller, the vehicle would read the current heading from the compass, compare this value with the desired heading, and maneuver until the desired heading matched the actual heading. To complete the integration process, a closed loop vision system was established. Real time camera data was continuously sent from the vision processor to the vehicle control board. The vehicle utilized this incoming information to determine its current location and maneuver according to the preprogrammed mission.

Conclusions

Functional and performance testing has shown the capability of the V-BASS to navigate through the speed gate, navigating through the channel while avoiding obstacles, and visually identifying targets of interest. The V-BASS vision system has the capability of identifying red, green, blue, and yellow buoys in direct sunlight and on cloud covered days. In addition to this, the camera can locate targets based on images saved to the system. The FAU RoboBoat team is presently continuing to develop the capabilities of the system in the lead up to the 2012 competition.