Ragin' Cajun RoboBoat–2021

Captains:
Adam Smith(Is he a captain?) and Joseph Stevens
Members:
Brennan Moeller, Nathan Madsen, Benjamin Willis
Coaches:
Joshua Vaughan[1] and Yasmeen Qudsi

Abstract— **This report discusses the motivations behind the design choices and improvements to the University of Louisiana at Lafayette's first entry to RoboNation's RoboBoat Competition which includes the addition of an Unmanned Aerial Vehicle (UAV). The overall function of this UAV is to act as a mobile sensor to survey the courses and record data with its onboard sensors including a RTK-GPS System, Raspberry Pi Camera Module, and OAK-D machine vision. The Ragin' Cajun RoboBoat is a catamaran-style autonomous surface vessel (ASV) equipped with four thrusters in an "X"-Configuration, enabling holonomic motion. The computer network communicates with individual components via the Robot Operating System (ROS). The contributions to the ASV from the 2021 Ragin' Cajun RoboBoat team include finishing the upgrades from 2020 that were hindered due to COVID-19, adding a Real-time Kinematic (RTK) GPS system, and upgrading the previous vision sensors to OAK-D machine vision sensors.**

I. Introduction

The 2021 RoboBoat competition requires teams to build an Autonomous Surface Vessel (ASV) capable of performing various tasks. For an ASV to accomplish these tasks, several subsystems must function together. The 2021 Ragin' Cajun autonomous system is shown in Figure 1. The ASV is equipped with two planar LiDARs and two OAK-D stereo cameras for machine vision feedback and a RTK GPS and an IMU for localization as shown in Figure 2. The vessel is equipped with four thrusters mounted in an "X"–Configuration, enabling holonomic motion. For the 2021 RoboBoat competition, the team has added an unmanned aerial vehicle (UAV) to be used as a mobile sensor, shown in Figure 3. The UAV is equipped with RTK-GPS, standard GPS, and an IMU for localization, OAK-D stereo camera for mapping, object recognition, and obstacle avoidance, and a Raspberry Pi Camera Module V2 (Pi Cam)for additional data collection.

[1]Department of Mechanical Engineering, University of Louisiana at Lafayette, Lafayette, LA 70504, USA joshua.vaughan@louisiana.edu

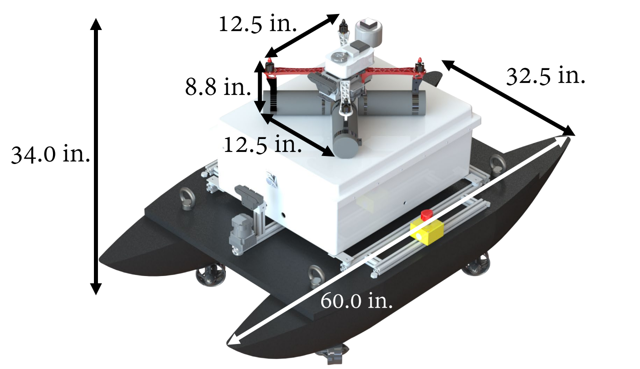

Fig. 1: 2021 Ragin' Cajun Autonomous System

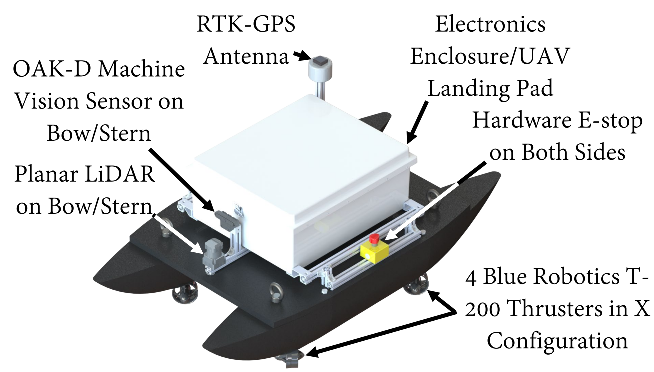

Fig. 2: 2021 Ragin' Cajun ASV CAD Model

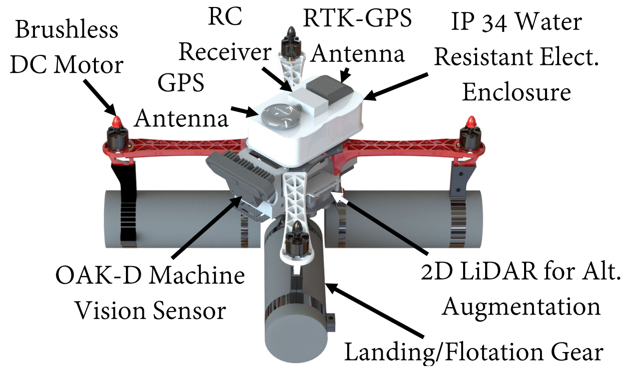

Fig. 3: 2021 Ragin' Cajun UAV CAD Model

This paper will discuss the competition strategy for the 2021 RoboBoat competition in Section II. Next, the design creativity of the main vessel and the new UAV will be discussed in Section III. In Section IV, the experimental results that were gathered will be presented. Finally, Section V is the conclusion.

II. Competition Strategy

The past competitions have shown that the Ragin' Cajun ASV is an adaptable and a capable vessel for RoboBoat's challenges, specifically the hull and thruster configuration. However, there was room for improvements including; utilizing a UAV in the competition, upgrading localization, and sensing components, and improving the control architecture of the system. This year integrating a UAV and upgrading the localization of the system was selected as the main focus. The following sections will discuss the strategic approach for the UAV integration and how the system will operate in the competition.

A. UAV Integration

There are many areas of improvement to be made to the 2020 Ragin' Cajuns' system including integrating a UAV to aid in the competition. Through an analysis of the past competitions, it was determined that this addition could allow the team to obtain approximately 1,200 additional points. The integration of this UAV to the current ASV requires tight integration of software and mechanical design. To facilitate the tight integration of the UAV's and ASV's sensing, mapping, perception, and controls, the Robot Operating System (ROS) is used. To ensure the designed UAV could be integrated to the ASV, CAD models of the UAV and ASV were created and updated throughout the process. This integration does increase the complexity of the system, but the ASV can operate independently of the UAV allowing for each run to continue even if the UAV fails.

For the 2021 competition, the main functions of the ASV will not change, but they will be improved with the addition of a UAV that will be used as a mobile sensor to collect data to assist the ASV in mapping, navigation, and localization. This UAV will be deployed after the mandatory Navigation Channel is completed and move to the next course. This will allow the UAV to be one course ahead of the ASV to collect data and place way-points, for the ASV to navigate towards, with increased accuracy due to the RTK-GPS system's correction data. The UAV is equipped with an OAK-D machine vision stereo camera for object recognition and obstacle avoidance as well as a downward facing Pi Camera for further data collection.

B. System Software

The multi-agent system presented in this paper utilizes ROS software packages including *robot_localization* and *rtabmap_ros* (Real-Time Appearance-Based Mapping). The first package is used to combine an arbitrary number of GPS and IMU sensors for state estimation [1]. *rtabmap_ros* is a global loop-closure Simultaneous Localization and Mapping (SLAM) package that allows for a stereo camera to create a 3-D point cloud of an environment. The maps created by the UAV and ASV will be compiled using a ROS package called $multirobot_map_merge$. This allows multiple maps from different robots to be compiled into one map. ROS is also used to aid in the overall communication of data for the system by allowing for multiple peripherals to share information across computers connected to a network. The *MAVROS* package is being used to communicate control messages to each of the flight controllers on the respective vessels in addition to communicating the data that is being recorded by the flight controllers. A mix of custom and standard packages are used to aid in the control, perception, and mapping of the system.

Due to the number of computational devices that are in this system and the different architectures of each device, Docker was used to create containers that could be implemented on multiple devices to speed up the initializing, booting, and configuring process. A Docker container contains all of the dependencies, packages, system tools, settings, and necessary libraries needed to execute an application. This allows for the same container to be ran on different operating systems such as the operating systems contained in the two TX2s or the two Raspberry Pis. Docker also allows for the code that is needed to execute certain tasks to be mounted to the container at time of use. This allows for the code to be saved to a platform like GitHub, so the development can be split across a team.

C. Navigation Channel

This task is mandatory and must be completed before attempting any other tasks. The complete system must pass through two sets of gates. Each gate consists of two buoys at least six feet apart. The two sets of gates are at least 50 feet apart. The Ragin' Cajun's RoboBoat is equipped with a forward facing stereoscopic camera that provides images to an image classifier trained by a Convolution Neural Network (CNN). The training set for this CNN consists of manually-labeled images from the previous competition, as well as images from the 2016 Maritime RobotX Competition. The output of the image classifier is made available to a state machine that determines how the ASV should maneuver. For the Navigation Channel task, the state machine directs the ASV to find a gate, identified with green in the right side of the frame and red in the left. A waypoint goal is sent to the navigation stack to maneuver to the middle of the gate and orient the vessel to be in-line with the channel. The state machine instructs the ASV to maintain the initial heading as it continues to drive forward and look for the exit gate. Another waypoint between the exit gate is sent to the navigation stack as a target location. As the vessel reaches this waypoint, it completes the Navigation Channel and prepares to launch the UAV.

D. Obstacle Channel

The obstacle channel requires the ASV to maneuver through a series of gates with obstacle buoys along the trajectory. Unlike the Navigation Channel, these gates are arranged in a non-linear path. This task may be difficult to complete because of the ASV's large footprint. However, the ASV is also equipped with a holonomic thruster configuration. This allows the ASV to exert forces and moments in each degree of freedom independently. Furthermore, it is equipped with a RTK-GPS system to help improve localization. This increased maneuverability, restrictions on maximum allowable velocities, and data collected by the UAV should aid the Ragin' Cajun RoboBoat to complete this task.

The UAV will launch, hover, and then will be tasked with finding the Obstacle Channel via GPS coordinates and object recognition. An outline of the UAV's state machine for the Obstacle Channel is shown in Figure **??**. The state *back_to_launching* will be invoked if the UAV cannot launch for any reason. Similarly, a redundancy is in place if the UAV cannot find the obstacle channel. There is a set limit that it can enter one of these redundancy states. This will aid the UAV from getting stuck in a loop. Once the UAV finds the Obstacle Channel, it will use the image classifier to follow the channel similar to how the navigation channel was identified, green in the right side of the frame and red in the left. The UAV will place Waypoints approximately in the middle of the channel as it flies above. This information will be available for the ASV through the ROS networking. There will be a message sent once the UAV exits the channel.

Once the ASV has arrived at this task, it will utilize the map created by the UAV with its path planning package, *roboboat_navigation*. This will allow the ASV to have an understanding of its environment before it gets to the channel as well as a desired path to follow through the channel. The vision feedback system provided to the navi-

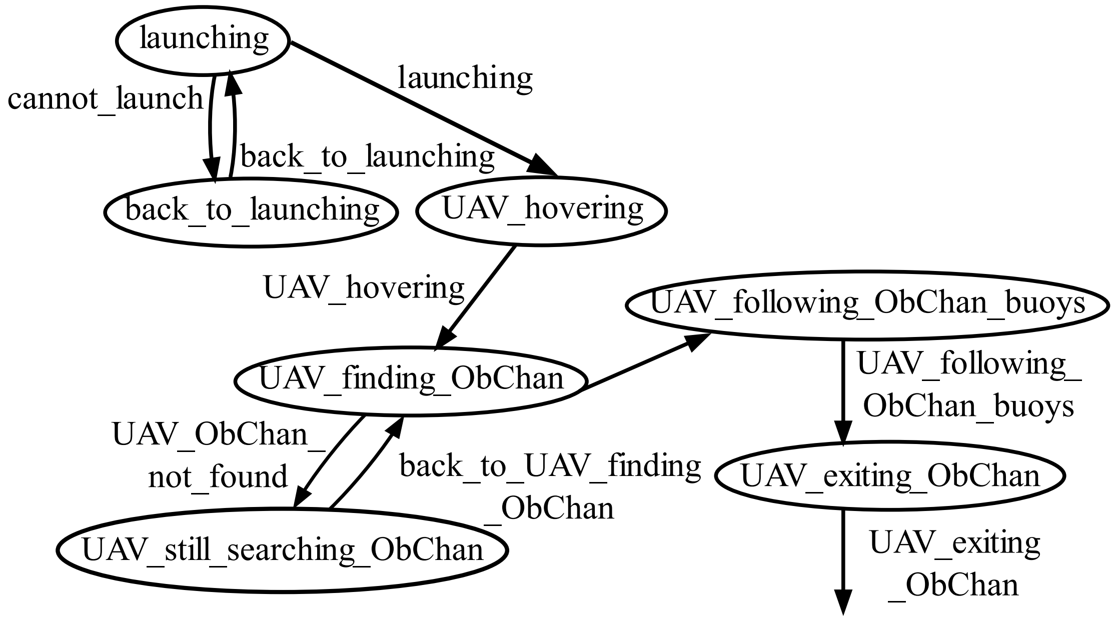

Fig. 4: State Machine for the UAV in the Obstacle Field Task

gation stack will prevent the ASV from colliding with the green, red, and yellow buoys. Similar to the Navigation Channel, the image classifier will be looking for green buoys in the left side of the image and red buoys in the right. If red and green buoys in the Obstacle Field are misinterpreted as gates, the path planner will prevent the ASV from entering a region that it cannot fit because it knows the base footprint area of the ASV.

E. Obstacle Field

Once the UAV exits the Obstacle Channel, it will move to the Obstacle Field to created a map for the ASV to use once it exits as well. The UAV will use the GPS coordinate as well as the image classifier to determine the location of the course. It will identify the pill buoy by identifying the an orange and blue colors in the frame. The UAV will then proceed to circumnavigate this buoy while updating the distances between the buoys to find the largest entrance and place a waypoint at that location. This waypoint will be accessible to the ASV's state machine to motivate it to move towards this opening.

When the ASV reaches the Obstacle Field, it will move towards the opening specified by the UAV. To ensure that it can fit through that opening, the ASV will also circumnavigate the Obstacle Field. The ASV will save the location of the entrance and enter. Next, the path planner will use both maps to plan a trajectory around the pill buoy. Once the Pill Buoy has been circled, and the ASV has changed its heading by at least 360°, the ASV will exit the Obstacle Field using the recorded position as the last waypoint and head towards the Speed Gate task.

F. Speed Gate

Once the UAV finishes mapping the Obstacle Field, the GPS coordinates will be sent to the Flight Control Unit (FCU) to motivate the ASV to move toward that location. As it approaches, the image classifier will be used to locate the one standalone gate that consists of one green and red buoy. The UAV will then hover and look for the mark buoy, a single blue buoy. It will then place a waypoint at the gate and fly toward the blue buoy where it will place another waypoint.

After the ASV completes the Obstacle Field, it will proceed toward the waypoint that was placed at the entrance of the speed gate. The state machine will override the velocity restrictions placed on the ASV by the path planner, so this task can be completed as quickly as possible. Then, the state machine instructs the ASV to pass through the gate at maximum speed. Once the target buoy has been located, waypoints are placed around it to it can be circumnavigated. The initial position at the gate is used as the final waypoint to guide the ASV out of the Speed Gate Challenge.

G. Return to Dock

After the UAV has finished all of the tasks, it will locate the ASV via its location in the course. The UAV will then fly towards this location, as it approaches the vessel the downward facing Pi Cam will identify an ArUco tag that will be on top of that ASV's enclosure shown in Figure 5. These markers allow for the cameras pose to be estimated. This information will be used so the UAV can know where it is in reference to the ASV. The UAV will follow the ASV to the starting position and then prepare to land. The UAV is equipped with a 2D LiDAR for altitude augmentation that will aid it in landing as well. With this estimation and the increased accuracy of the RTK-GPS system, the UAV will then slowly approach the lid of the enclosure. Once the UAV is approximately 4in from the lid of the enclosure, the UAV will land.

After the ASV finishes the Speed Gate challenge, it will navigate back to the starting location that was recorded upon entering the course. Throughout the competition, the ASV will be creating a map of the course by recording all of the obstacles location and features. Along with the ASV's localization and path planning capabilities, this map will be used to maneuver it back to the starting position without encountering any of the obstacles or exiting the course. Once the ASV reaches the dock, it will hold its position with the help from its navigation stack to allow for the UAV to land on top of it.

H. Acoustic Docking

This task requires a vessel to localize a docking signal and dock itself in the specified docking bay. The 2021 Ragin' Cajun RoboBoat team declined to continue to develop upon the previous system used for this task. The focus was moved to the design, manufacture, and integration of the UAV

Fig. 5: ArUco Marker On Top of ASV to Aid in Landing

to the ASV system. Also, due to COVID the 2021 Ragin' Cajun RoboBoat team needed to finish some of the improvements that were not able to be made in 2020 because of COVID-19 restrictions including completing the addition of the new electronics enclosure and addition of the stern LiDAR and stereo camera.

I. Object Delivery

This task requires the ASV to deliver up to four objects to a specified area in the course. The task may be completed solely by the ASV or by a combination of an ASV and UAV. The 2021 Ragin' Cajun RoboBoat team declined to develop the required mechanism to complete this task. However, the frame selection and custom frame plates for the UAV were designed with additional mounting holes to allow for further development. This will allow future teams to develop subsystems as needed.

III. Design Creativity

A. Thrust Configuration

The thrusters are configured in an "X" pattern, and mounted at 45° angles, relative to the bow. A free-body diagram of this thruster configuration is shown in Figure 6 This enables holonomic motion, or motion in all three degrees of freedom independent of each other. This improves the maneuverability of the ASV through tasks like the Obstacle Channel or Obstacle Field. It could also assists in docking for future competitions since the ASV can move in the positive or negative sway

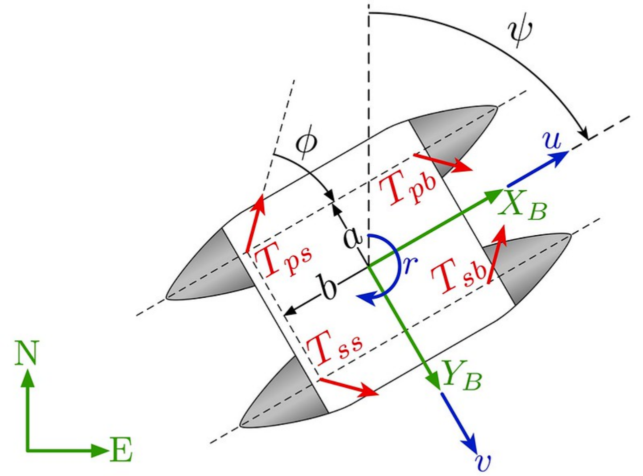

Fig. 6: Free-Body Diagram of RoboBoat Thruster Configuration

directions and does not have to do a forward–reverse maneuver, such as a car parallel parking.

Though this thrust configuration was used on the past Ragin' Cajun RoboBoat entry, its performance has shown that for this system it is still sufficient. Furthermore, the addition of the RTK-GPS system that receives RTCM (Radio Technical Commission for Maritime-services) data to increase the accuracy of standard GPS signals to centimeter levels allows for the ASV to increase its localization capabilities [2]. This specific thruster configuration allows the ASV to take full advantage of the increased localization by its ability to move in every degree of freedom independently.

B. UAV Center of Mass

To achieve desired stability during flight, the UAV's center of mass (COM) had to be considered. Throughout the design of the UAV, component placement was driven by the effects that the location and mass of these components would have on the COM of the UAV. The location of the COM in reference to the horizontal plane in which the rotors lie has an affect on the stability of forward flight and the UAV's ability to combat wind disturbances [3]. For this application, it was determined that a COM below the horizontal plane in which the rotors lie was more desirable. This location of the COM tends to have a positive

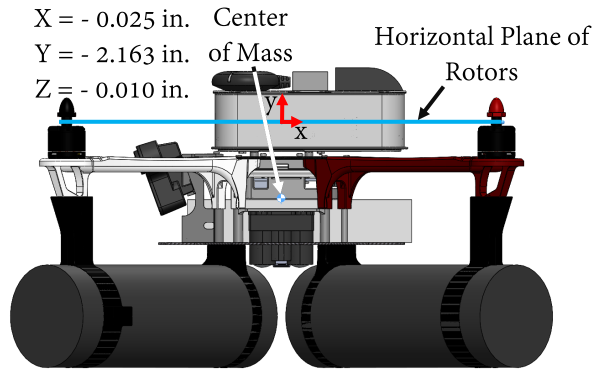

Fig. 7: UAV Center of Mass

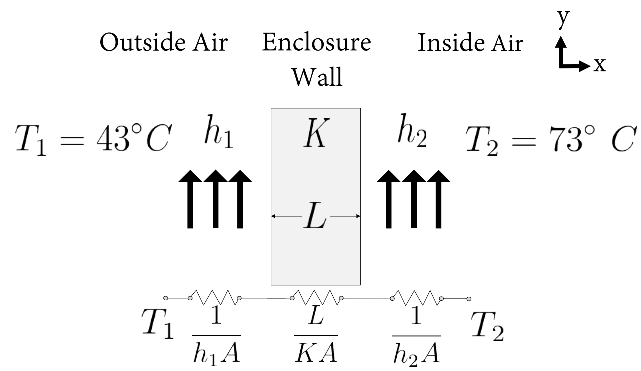

Fig. 8: Model of Simple Heat Transfer Problem

result on forward flight stability [3]. In its current state, the location of the UAV's COM, relative to to the center of the horizontal plane in which the rotors lie, is (-0.025, -2.163, -0.010)in shown in Figure 7. As previously stated, the UAV's desired COM drove the placement, mount design, and selection of the components.

C. UAV Enclosures

Being that the RoboBoat competition takes place regardless of weather conditions, it was imperative to keep all electronics safe. This was achieved by fully enclosing them in 3D printed enclosures. These enclosures would also be used to directly mount the electronics to the UAV. It was determined that all enclosures must meet Ingress Protection (IP) 34 standards, water resistant from splashes of water in all directions. To ensure that the main electronics would not overheat or be introduced to throttling, heat transfer calculations were done. The problem was modeled as a thermal resistance problem, as seen in Figure 8. T_1 represents that hottest temperature that Florida

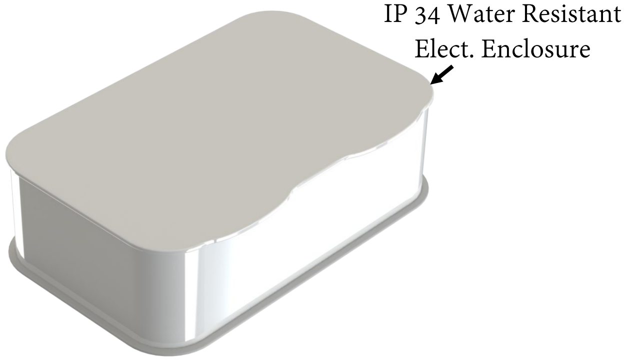

Fig. 9: Main Electronics Enclosure

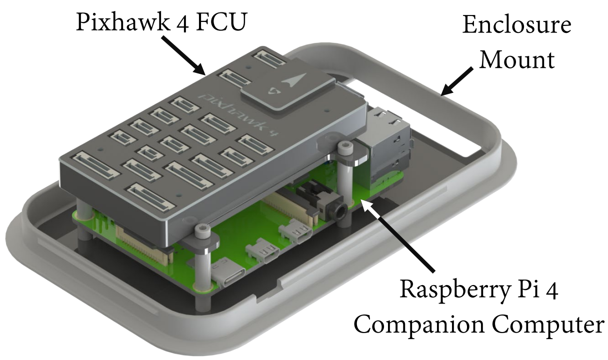

Fig. 10: Main Electronics Mount

has ever reached and T_2 represents the average operation temperature of Raspberry Pi which is 20-30°C above the ambient operation temperature [4], [5]. This calculation determined that the system would dissipate heat to the environment through the enclosure, but more importantly that the Raspberry Pi's CPU would not reach its throttling temperature, 85°C. The main enclosure would be made of acrylonitrite butadiene styrene (ABS) because of its UV and weather resistant properties shown in Figure 9. In Figure 10, the main electronics in this enclosure include a Pixhawk 4 Flight Control Unit (FCU) and a Raspberry Pi 4 companion computer. Further considerations were made to ensure other electronics be protected from water ingress such as the Pi Cam, RTK-GPS, and power module. The LiDAR Lite V3HP equipped on the UAV already exceeded the desired qualifications with an IPX7 rating.

D. UAV Landing Gear & Flotation Device

The 2021 RoboBoat rules require that any UAV that is used in the competition be positively buoy-

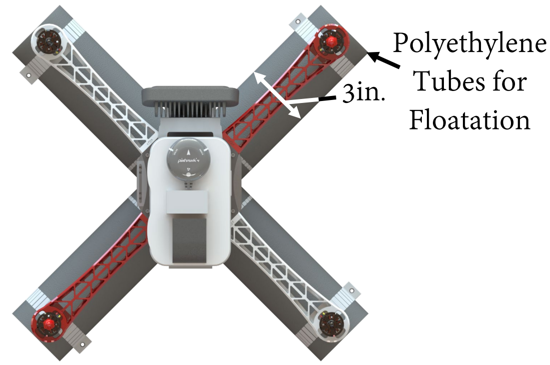

Fig. 11: UAV Flotation/Landing Gear

ant. This is a difficult challenge to achieve for a UAV that is being modified for data collection due to the additional weight added by the sensors. Another challenge is ensuring that the device does not obstruct the flow of air to the rotors. Three designs were considered including spheres on the feet of the frame, a square tube around the perimeter of the UAV, and cylindrical tubes in an "X" configuration under the UAV. These designs each had advantages and disadvantages; however, the chosen design, due to its ease of assembly, least air flow obstruction, and its ability to be adjusted, was the cylindrical tubes in "X" configuration, as seen in Figure 11. The cylindrical tubes used are industrial, polyethylene backer rods. This flotation device is also suitable for landing the on ASV or solid ground.

E. Data Acquisition

1) Raspberry Pi Camera Module V2: A Pi Cam was positioned on the bottom plate of the UAV to be used as a downward facing image sensor to collect data for object detection and landing procedures. As with all components added to the UAV, multiple design challenges had to be overcome with a creative approach to ensure proper component placement. These challenges included affects on the COM, mount design to minimize weight, and placement to reduce the interference with other components. As seen in Figure 12, a sketch showing the analysis of the horizontal (largest) field of view (FOV), 62.2 degrees, of the PiCam can be seen. This shows a successful design insuring correct measures be

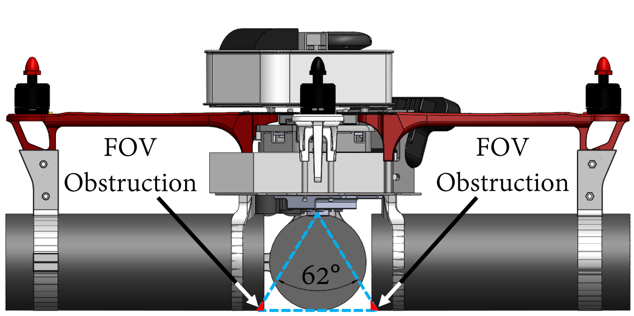

Fig. 12: Raspberry Pi Camera Module V2 FOV

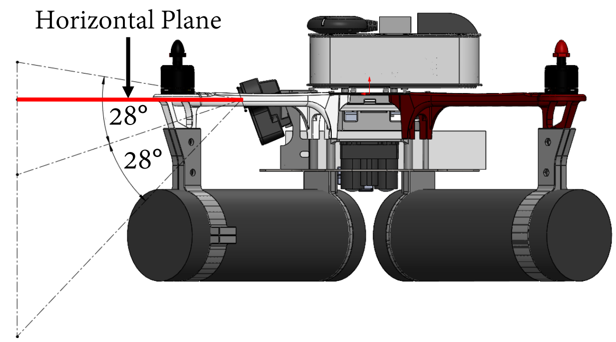

Fig. 13: OAK-D Field of View

taken to avoid FOV interference by the flotation device. As seen in Figure 12, a small amount of the polyethylene foam was expected to cause a slight interference in the camera's FOV. However, this amount of interference was later determined to be insignificant during testing.

2) OAK-D FOV: As seen in Figure 13, an OAK-D stereo camera will be used to capture distance and RGB image data for purposes of mapping, object detection, and obstacle avoidance. During the design process, the placement of all image sensors used on the UAV needed to be closely analyzed to insure proper and consistent image data collection. The image sensor's FOV, mounting, and data type governed the orientation and location of these sensors. Moreover, these factors drove the design of their mounting hardware. As seen in Figure 13, the vertical FOV of the OAK-D stereo camera was sketched and analyzed. The OAK-D has a vertical field of 56 degrees. It was determined that the forward facing camera mount which holds the OAK-D on the UAV would need to be designed with a 20 degree angle from the vertical, as seen in Figure 14. This mount also locks the cameras position on the UAV allowing for the exact location to be known when the camera is collecting data. As seen in Figure 13, this design gives the OAK-D the capability of capturing image data above and below the horizontal plane providing data for both obstacle avoidance and object recognition, respectively.

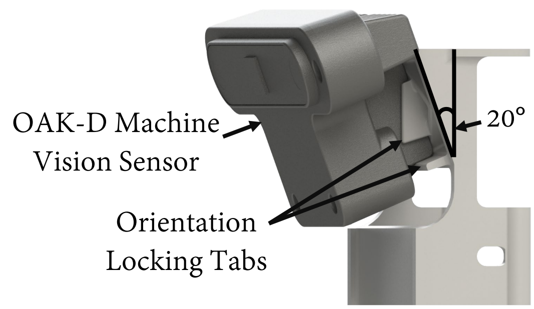

Fig. 14: OAK-D Camera Mount

IV. Experimental Results

The experimental tests that were conducted for this system include a mixture of physical and simulated test. The UAV was integrated into the RotorS Micro Air Vehicle (MAV) Gazebo simulator [6]. This simulation allowed the ROS packages and scripts that would be needed for the perception sensors and mapping algorithms on the UAV to be tested. Physical tests on the system included testing buoyancy, the IP rating of the electronics enclosures, and the RTK-GPS accuracy for the Ragin' Cajun RoboBoat system.

A. System Simulation

The UAV was imported into a simulator called RotorS because of its use of a physics based ROS application called Gazebo. This means that all forces can be applied to the UAV to simulate a real world environment. There are also parameters to simulate noise in the system. Each sensor that is on the UAV can also be simulated such that the FOV and data being collected represent that of the actual sensor. There are many environments that come pre-installed with RotorS, and there are many more that have been created that can be used with RotorS. For the beginning stages of import-

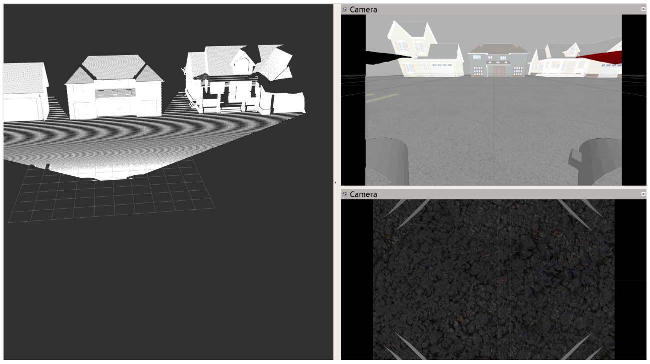

Fig. 15: UAV Peripheral Simulation in RViz

Fig. 16: Testing of Flotation Device

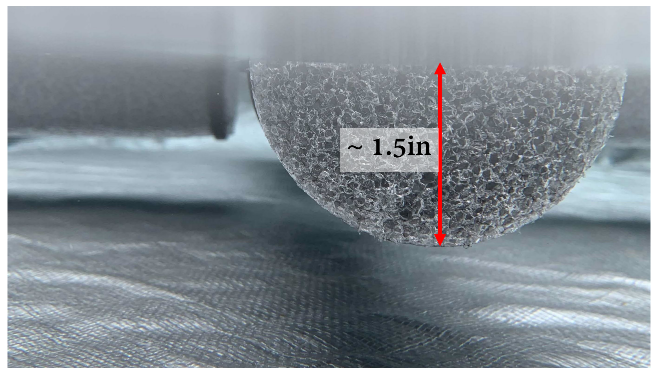

Fig. 17: Submerged Flotation Device

ing the UAV into RotorS, the basic environment was used. In this simulated environment, all of the sensors were configured to accurately represent their specifications. In RotorS, flight paths can be set, scripts that would control the perception and mapping algorithms can be executed, and data can be collected, as seen in Figure 15. Figure 15 shows depth data collected by the simulated OAK-D stereo camera on the left and RGB image data collected by the simulated OAK-D digital camera on the top right. The bottom right image in Figure 15 displays RGB image data collected by the simulated Pi Cam. This simulation will allow for future development to occur for the UAV without having to carve out time to physically test the UAV in an open area.

B. Buoyancy Test for the UAV

To ensure the flotation device was properly designed, testing was conducted in a controlled environment. The completely loaded system, including the battery and all fasteners, was placed in a controlled body of water to analyze if it would float. As seen in Figure 16 the UAV is floating. Figure 17 shows the submerged amount of the flotation device was approximately half of the tube, 1.5in. The testing on the flotation device was considered a success due to this fact.

C. IP Rating Test

Since the IP rating for the electronics enclosures on the UAV were designed IP34 standards, testing was conducted to ensure ingress protection from splashes of water in all directions. The test was conducted by first adding a piece of a hydrophilic material within the enclosures to ensure any water that could leak in would visible after testing. Then, a silicone bead was placed around the lip of the encloses and around any exposed wires to seal off any openings. Next, a 12oz. water bottle was modified to allow for a stream of water to be sprayed from it. Finally, the enclosures were placed on a pedestal and sprayed from all directions ensuring water touched every surface. The results for the main electronics enclosure are displayed in Figure 18 and all of these tests showed that the designed IP34 rating was met.

D. RTK Accuracy

To increase the accuracy of the UAV and ASV, Real-time Kinematic (RTK) positioning was used. With RTK, the accuracy of the system has the possibility of increasing to centimeters of accuracy versus standard GPS which has roughly a 16ft. radius of error. The accuracy associated with an RTK system is relative to time and the number of satellites and base stations in the area. The RTK system for the Ragin' Cajun RoboBoat will

Fig. 18: Submerged Flotation Device

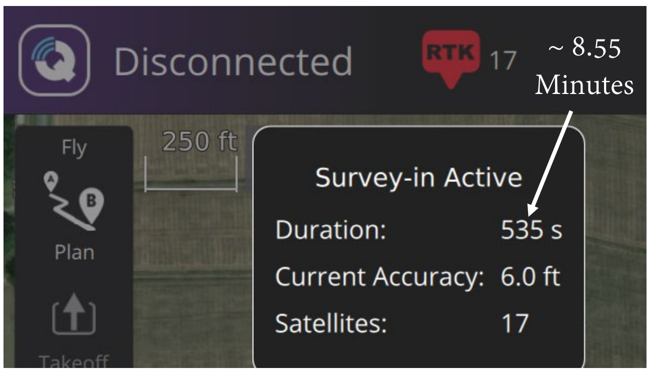

Fig. 19: RTK Accuracy with QGround Control

consist of one base station that has a fixed location on-shore and two rovers that are on each of the systems, respectively. To examine the RTK system under a time crunch, a test was done to see how accurate the base station could get in a 10 minute time frame. As seen in Figure 19, in under 9 minutes the accuracy of the system was able to get down to 6 feet. This is not centimeters of accuracy, but it is better than a 16ft. radius of error. Furthermore, by increasing the time that the RTK system is allowed to hone in its signal, its accuracy can be improved.

V. Conclusions

This paper analyzed the design of the 2021 Ragin' Cajun RoboBoat system, including key software, hardware, and strategic improvements. This design builds on the Ragin' Cajuns' previous entry to the RoboBoat Challenge and now includes a UAV to aid in data collection throughout the courses, upgraded OAK-D machine vision sensors, and a RTK-GPS system for increased localization accuracy. Contributions made by this team to furthering the Ragin' Cajun RoboBoat development at the University of Louisiana at Lafayette include a Gazebo simulation of the UAV, an updated CAD model of both systems, and a platform to attempt more task in the future including the Object Delivery task. The Competition strategies employed and documented, upgrades to sensors, and the addition of the UAV by this team may be useful to future Ragin' Cajun RoboBoat team members.

VI. Acknowledgments

This project would not be possible without the guidance and support of our Coach, Dr. Joshua Vaughan and Yasmeen Qudsi. The team would like to thank them for their patience with us and willingness to assist us wherever possible. The 2021 Ragin' Cajun RoboBoat team would also like to thank Chapman Consulting Inc. for allowing us access to their facilities and resources. Also, the team would like to thank OpenCV, Luxonis, and Intel for sponsoring the OAK-D AI Competition which allowed us to win 10 free OAK-D machine vision sensors.

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APPENDIX

TABLE I: Ragin' Cajun RoboBoat Specifications

Category	**Item**	**Vendor**	**Specifications**	**Quantity**	**Price ($)**
Actuation	HDA4-2	ServoCity	4" Stroke 25lb Thrust	1	129.99
Battery	4S Li-Po	Turnigy	16V 5200 mAh 450g	4	53.96
Battery	3S Li-Po	Floureon	12V 4500 maH 324.5g	2	33.29
Battery	3S Li-Po	Zeee	12V, 100C 9000 maH 560g	2	71.00
Comm.	TL-WA901ND	TP-Link	2.4-2.4835 GHz 270m range 12V, 1A 5.8W	1	37.99
Computing	Pi 4B+	Raspberry Pi	ARMv8, 1.5 Ghz 8GB DDR4 RAM	1	90.00
Computing	Jetson TX2	NVIDIA	256 CUDA Cores 2-Core Denver 2 4-Core Cortex-A57 8GB DDR4 RAM	2	629.99
Control	NAVIO2 HAT	EMLID	5V, 150 mA Cortex-M3 IMU, Barometer	1	168.00
Control	PX4 FMU	Holybro	5V 2 Accel/Gryo Barometer	1	245.00
Enclosure	PJ24208RT	Hammond MFG	0.064 m^3 Fiberglass 11 kg	1	Donated

Hull	Fiberglass Cloth	TotalBoat	$6\ \frac{\text{oz}}{\text{yard}^2}$	$10.56\ \text{yard}^2$	56.01
Hull	Epoxy	TotalBoat	$1.18\ \frac{\text{g}}{\text{cm}^3}$	4.31 kg	126.99
Hull	Fairing Compound	TotalBoat	$1.32\ \frac{\text{g}}{\text{cm}^3}$	2.27 kg	56.99
Propulsion	T-200	Blue Robotics	$[-4.1, 5.25]$ kgf 76mm Propeller 156g (in water) 390W, 24A (max)	4	169.00
Propulsion	Speed Controllers	Blue Robotics	16.3g 7–26V 30A (max) $[1100, 1900]\ \mu$s	8	25.00
Propulsion	MT 2213 Motor 1045 Propeller	EMAX	935KV, 860g thrust 1045 Propeller	4	67.00
Sensing	H2C Hydrophone	Aquarian Audio	$(0.01, 100)$ KHz 0.3mA 2KΩ Impedance Omnidirectional 25mm x 58mm 51g $\leq$80 meters	2	169.00
Sensing	Scarlet 2i2	Focusrite	$(0.02, 20)$ KHz 1.5MΩ	1	159.99
Sensing	GPS-RTK Board	SparkFun	5V, 35mA 5Hz-RTK NEO-M8P-2	3	199.95
Vision	UTM-30-LX-EW	Hokuyo	270° FOV 2D Projection 30 meter range 100 Hz	2	4900.00
Sensing	LiDAR Lite V3 HP	Garmin	1m-40m, 5V 85mA	1	150.00

Vision	Camera Module V2	Raspberry Pi	8 MP Sony IMX219 62.2°, 48.8°	2	25.00
Vision	OAK-D Stereo Camera	Luxonis OpenCV	1MP 1280x800 120 FPS 900mA / 5V 115g 81°, 71.8°	2	Won
Vision	OAK-D RGB Camera	Luxonis OpenCV	12MP 4@K30 FPS 900mA, 5V 115g 81°, 68.8°	2	Won
Frame	F450 Quad-rotor	DJI	450mm footprint	1	72.00