Development of the Minion ASV for the Maritime RobotX Challenge

Embry-Riddle Aeronautical University Team Minion
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Abstract

Embry-Riddle Aeronautical University has been selected as one of three schools to represent the United States in the inaugural Maritime RobotX Challenge. This challenge requires the development of a fully-autonomous surface vehicle using the 16-foot Wave Adaptive Modular-Vessel (WAM-V) platform. The platform must be capable of autonomous operation in cluttered dynamic environments requiring sophisticated path planning, obstacle avoidance, object detection, object classification, and sensor fusion algorithms. This paper discusses the novel software/hardware approach taken, and the challenges that arose during the development of the Minion ASV platform. Sensing for Minion is achieved by fusing data from a Velodyne HDL-32E LIDAR with two Microsoft LifeCam wide angle cameras via a persistent Mapper Module which dynamically updates Minion's view of the world. To detect objects below the water Minion has an array of four deployable hydrophones attached to a high sample rate data acquisition system. This data is filtered and analyzed to allow for localization of a known acoustic emission source. All of Minion's systems are rated to survive operations in adverse weather conditions including high heat, high humidity, and heavy rain storms. This was achieved using commercially available hardware and connectors; this has the added benefit of allowing hardware to be interchangeable. Minion is propelled using a disturbance rejecting Linear Quadratic Regulator control scheme driving a pair of Rim Driven Propellers.

Introduction

Figure 1 Minion ASV undergoing testing

The Embry-Riddle Aeronautical University (ERAU) Team working on the Maritime RobotX challenge consists of students ranging from undergraduates to Ph.D. students with backgrounds in Software, Electrical, and Mechanical Engineering and experience working on multiple AUVSI Foundation Competitions. This experience has led to the design and testing strategy of the ERAU RobotX platform, Minion (Figure 1). From the outset Minion was designed to be rugged, robust and upgradable. To achieve this Minion was constructed with multiple safety systems, water resistant construction, and commercially available hardware. This allowed the team to begin testing early and in varying weather conditions.

The Minion system, Figure 2, is based on a novel, modular hardware/software design. This architecture is fully networked with an interchangeable, upgradeable sensor package and service-oriented software that provides a high level of both flexibility and reliability. Communication, control, and health monitoring are implemented using an Ethernet-based backbone distributed across multiple computers with a publisher-subscriber paradigm. The hardware on Minion consists of commercial off-the-shelf sensing and ruggedized computing hardware with software modules that are abstracted to allow the use of each sensor's data in different applications.

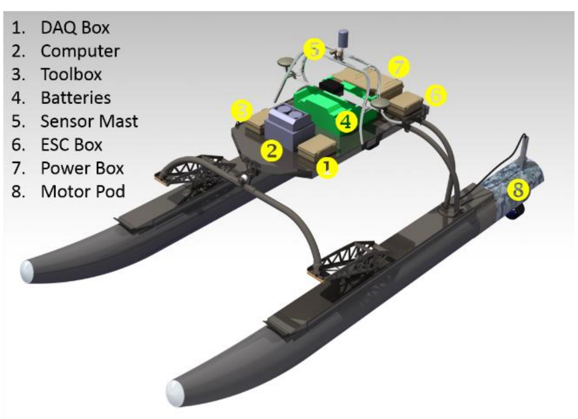

Figure 2 Minion general arrangement

Minion's propulsion system consists of a pair of fixed electrically-powered rim-driven propellers (RDP), shown in Figure 3, which offer a 7.5 knot top speed with low energy consumption while minimizing the potential for ingesting debris, and maximizing safety to personnel and marine life. In order to eliminate potential points of failure incurred by a steering mechanism and simplify operation, Minion steers using the differential thrust between the two RDPs to create a moment to yaw the platform.

Figure 3: Rim Driven Propeller (RDP)

Technical Approach

Minion is a highly integrated autonomous system featuring a multi-tier failsafe system, weather tight (IP 65 or higher) components, 3-6 hours of run time depending on operating conditions, and a modular sensor suite. The sensor suite is flanked by a ruggedized dual antenna GPS/INS system for localization, hydrophones for detecting submerged acoustic sources, a 360 degree field of view laser range finder (LIDAR), and dual mounted front-facing cameras for perception. System propulsion and sensing are tied together through a novel software architecture that classifies and maps objects based on sensed data, which are fed to an objective tracker and path planner for generating trajectories and ultimately motor commands.

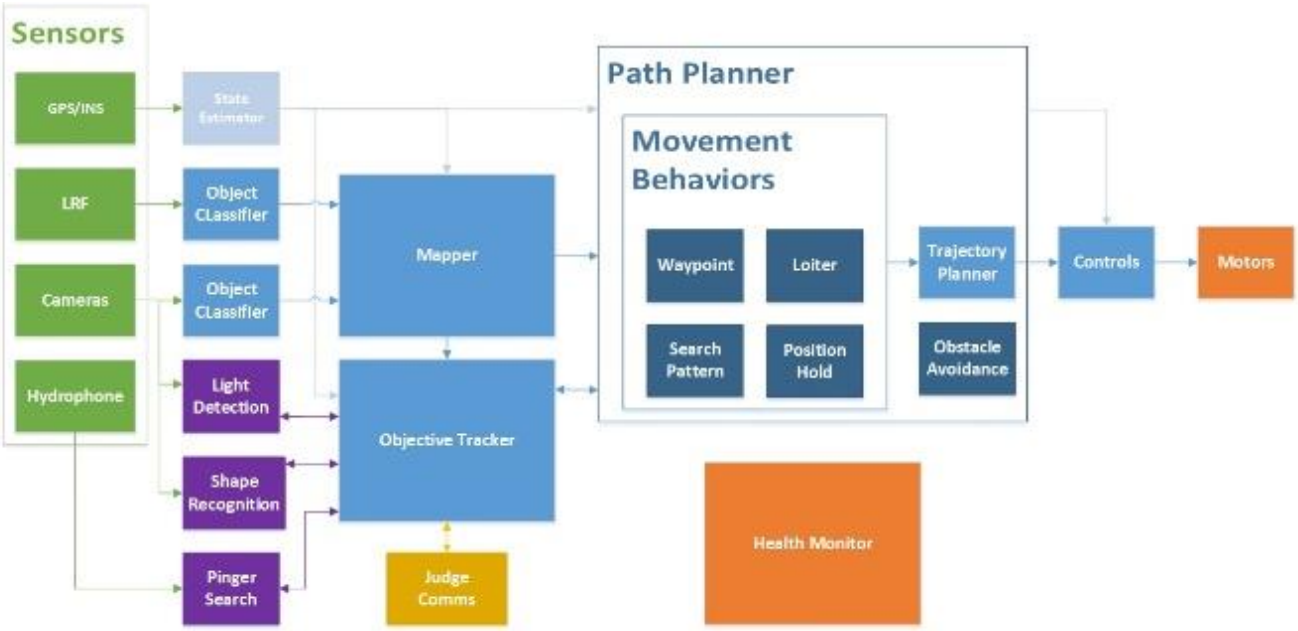

Figure 4 Minion's software architecture

Software Architecture

Minion’s software architecture uses an event driven, self-monitoring, distributed computer structure designed to allow for the buildup of features, a process called complexity through iteration. Minion is capable of multi-sensor state estimation, variable autonomy modes, intelligent trajectory planning, environmental disturbance rejection, external communication to multiple targets, and intelligent tasking.

This software architecture seen in Figure 4 consists of a set of independent modules running as separate processes. Each of these modules takes in data using a subscription, meaning it only listens to certain types of data, and then tags outgoing data for consumption by other modules, known as publication. Once these modules have passed a base level of performance and have been tested in both software-in-the-loop and hardware-in-the-loop testing they are integrated into the main platform and field tested.

The onboard computing solution for Minion is a ruggedized APlus Mobile S-320. This computer consists of four independently powered multi-threaded CPUs networked over an internal Ethernet switch and contained in an IP67 housing with integrated cooling. In order to increase the robustness and platform availability, each software module is compiled as an independent executable and run on one of the four Windows 7 computers. This allows for the restart of individual modules or entire nodes of software without impacting the performance of separate standalone modules. To ensure that each of the Windows installations remains stable in the event of unexpected power cycling, the operating system partition of the hard drive is protected using Deep Freeze software to lock the critical file system image.

Regardless of the mode or mission segment, Minion executes all software nodes in parallel and asynchronously. Data from the position sensors is fused with data from the LIDAR and cameras in the Mapper where they are stored in the global reference frame. The Mapper feeds this information into the Path Planner which in conjunction with the Objective Tracker selects the appropriate behavior i.e. waypoint or loiter. The Mapper Module publishes a list of all pertinent objects in the vicinity of the platform, allowing the Path Planner to generate a drivable path. This trajectory is then checked for obstacle intersections. If an intersection is detected, Minion dynamically generates a new trajectory around the obstacle while maintaining the desired heading and velocity towards the desired end point. Finally this trajectory is fed into the Controls Module that uses a tracking algorithm in combination with a dynamic disturbance rejection algorithm to follow the desired path while compensating for environmental disturbances.

Safety Systems

With any large vehicle safety is the primary concern, more so when the vehicle is autonomous. The safety systems on Minion were the first thing to be installed and have been rigorously field tested over nine months of trials. Minion has a multiply redundant failsafe safety system. This tiered system consists of both a remote and local safe stop systems. The hard stop system consists of commercially available mushroom buttons located on the uprights of the WAM-V platform and RC link-loss detection hardware. The hard stop systems are hardware-only and bypass all software systems. The soft stop systems consists of safing switches located on the ground control station software and the remote control. In either case, electro-mechanical contactors disengage to cut power to the propulsion system while leaving the onboard autonomy package powered and allowing for a predictable return to either autonomous operation or user control. The onboard soft stop is also engaged in the event Minion crosses one of its geo-fences indicating it has left the safe area of operation.

Health Monitoring

Minion has a sophisticated onboard health monitoring system that incorporates lessons learned from previous AUVSI Foundation competitions. The Health Monitor tracks the operating state of mission critical modules and provides centralized handling of software and hardware errors. Current and voltage sensors track the operational state of hardware while Process Monitors on each computing node provide for heartbeat detection, state tracking, and automatic restart of software modules. In the event of a hardware failure Minion is able to power cycle individual systems, components, or computers. External indication of Minion’s current state is proved by an IDEC light tower that indicates if the platform is powered, under user control or autonomous, and the state of the emergency stops.

Communication Systems

Through experience garnered from multiple AUVSI Foundation competition entries, ERAU has developed a highly reliable, all weather Wi-Fi communication system, which is integrated directly into Minion's Ethernet backbone. This data link consists of a pair of Ubiquiti Rocket multi-antenna radios with diversity. These radio's transmit at 2.4 GHz for communications with the judges and 5.8 GHz for one way communication from the ground station to Minion. This data link has been extensively tested in RF hostile environments and at ranges and power settings similar to those in the Maritime RobotX Challenge.

An independent direct command and control link is maintained with Minion at all times using a frequency hopping, spread spectrum, commercially available long-range RC system. This system has the ability to command the platform to move from manual mode to either a paused state or an autonomous run mode as well as command the vehicle's emergency stop functions.

Perception

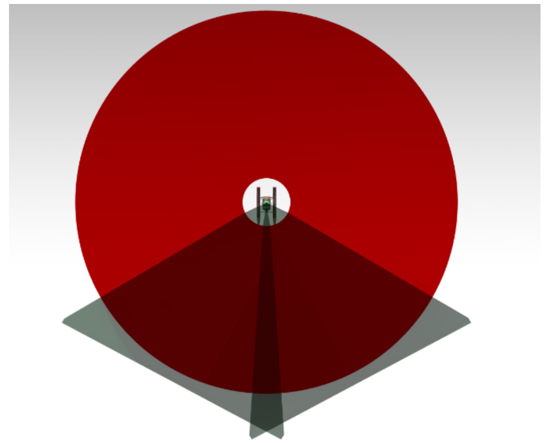

Figure 5 Minion's sensor horizon showing LIDAR (red) & cameras (grey)

Minion uses multiple sensor modalities, as illustrated in Figure 5, giving the platform a full 360 degree view of its environment both above and below the water's surface. Primary exterioceptive sensing is accomplished using a Velodyne HDL-32E LIDAR in conjunction with a pair of wide-angle Microsoft LifeCam cameras. Localization is provided using a TORC PinPoint containing a combination of a high precision Inertial Measurement Unit (IMU) and dual-antenna GPS. Acoustic data is collected using four hull-mounted deployable Sparton hydrophones connected to a high speed data acquisition system. All of this data is processed by sensor-specific modules and the filtered results are sent to the Mapper Module to be stored for use by the Objective Tracker, Path Planner, and Movement Behaviors.

LIDAR Perception and Classification

The Velodyne HDL-32E LIDAR operates using a cluster of 32 infrared (IR) lasers which yield

700,000 points/second ranging from 10 degrees above horizontal to 30 degrees below in a 360 degree swath around the platform, as shown in Figure 6. An advantage to using IR lasers in the maritime domain is the poor reflectivity of 905 nm IR sources in water. The water yields very poor returns, enabling rapid and accurate discrimination of objects such as the buoys. LIDAR also allows for accurate determination of range for tasks such as docking.

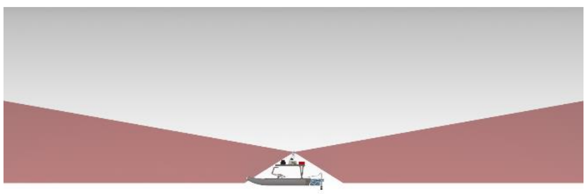

Figure 6 LIDAR elevation on the Minion platform

In order to quickly sort, associate and expand stored information, all measured and calculated data is stored in arrays. Each element in these arrays is associated with a location around Minion. The elements are 0.1m x 0.1m squares covering a 24m x 24m area surrounding the vessel. To detect and classify objects of interest there are currently three arrays being created; an occupancy grid, count of returns from a location and a count of rings from the LIDAR that returned at a location. The occupancy grid array is created as an image to utilize OpenCV features such as blob detection and edge detection to discover and number objects seen in a scan. Each object's pixels are stored with the object, making it easier to locate information about that object through array indexing.

Objects that meet a list of criteria (such as roundness or height) are sent to a Multivariate Gaussian Classifier to determine the objects type. Currently Minion will classify all objects as four different types, tall buoy, small-round buoy, light tower and unknown. Objects of interest, such as the tall buoys, within 24m are classified as something other than unknown 90% of the time, and through extensive lab and field testing have shown to be 98% accurate in that classification.

Camera Perception and Classification

The cameras on Minion are angled off-center to create a 120 degree field of view with a 6 degree overlap. Each camera captures a 1920 x 1080 pixel image at 30 frames per second. The advantage of the higher resolution is Minion can look at objects far away with great detail. Unfortunately, having two large images is difficult to process in real-time. To solve this Minion uses a clever scheme, in which it creates dynamic regions of interest (ROI) around the objects it wishes to gather more information on. These ROIs are created using information from the mapper module about the objects global location. This location is rotated and translated into the camera's frame of reference and associated with a rectangle of pixels from the large image. The ROI is a much smaller image and therefore can be processed with more advanced techniques in real-time.

Minion gathers information on multiple objects including buoys, dock targets and the light tower. To determine the color of the different types of buoys the maximum and minimum value from the RGB color planes are subtracted from one another, enhancing the brightest pixels in the image. Then a check is made to determine if the background of the image is brighter than the object of interest. This happens often when Minion is facing into the sun, and will enhance the water instead of the buoy as seen in Figure 7. If Minion concludes that the enhanced part of the image is not the object of interest, then the image is inverted. A threshold is then applied to create a mask for use in color detection. A histogram is run on the ROI using the mask to determine the color.

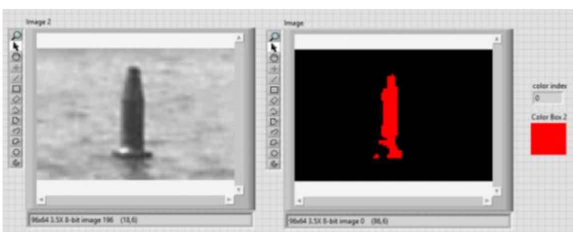

Figure 7 ROI segmentation and color detection

This algorithm is applied to both buoy and light tower color classification. To determine the sequence of the light tower each color classification is logged. After each log a check is run to see if the last four values are a valid sequence. If the sequence is valid then the objective tracker is flagged and the final sequence is sent out.

Hydrophone Localization

Minion is equipped with four Sparton PHOD-1 Hydrophones connected to a high speed data acquisition system. This allows the platform to perform passive sonar localization. When localizing, the platform lowers the hydrophone array and disengages the motors. The platform listens for pings for approximately 30 seconds before raising the array and moving to a new location. This process is repeated until 4 locations are recorded. The data is then analyzed using a combination of band and noise filters and time difference of arrival measurements. From this the location and depth of the ping source is triangulated. Once the source is located, further readings can be taken to improve the accuracy of the result. After a result with a satisfactory error is achieved the module reports the all clear to move on to the next task.

Mapping

In order to better make use of the data supplied by its sensors Minion creates a persistent map of its surroundings. This requires that the data collected by the sensors in a North-East-Down geo-referenced local frame be transformed to the global frame, which is referenced to the geographic datum. The Mapper Module is responsible for performing this transformation and stores a global frame referenced map.

The Mapper Module uses three distinct phases to generate Minion's persistent view of the world. First is the Create Phase, in which Minion reads data from its sensors and creates objects for each item the sensors detect. Next in the Update Phase, the objects instantiated in the Create Phase are checked against the list of known existing objects. This check takes into account the instantaneous error in measurement and the known motion of the existing objects in relation to Minion. If the newly created object falls within the error bounds of an existing object they are merged. Finally the Mapper Module enters the Delete Phase; here the Mapper checks to see how many times each object has been sensed. Objects that are sensed repeatedly in a location, given the uncertainty ellipse of the measurements, are given a higher confidence of existing, otherwise the confidence in that object existing decreases. If the object's confidence value drops below a threshold, it is deleted. This data is then updated to the current list containing each object, its classification, unique ID number, and whether or not it is a dynamic object (a chase boat) or a static object (a buoy). Static objects are given object permanence, meaning that if they are not seen because of an occlusion or limited sensor range their confidence value is not decremented in the Delete Phase.

Path Planning

Minion implements a dynamic iterative path planning algorithm based on a Dubin's car model of vehicle motion[1]. The path planner uses state information from the Mapper Module (global data), and the vehicle state (local data), together with the objective to be tracked and computes the shortest distance and shortest time paths. These paths are generated using multiple velocities with the shortest path being selected based on the time to completion (Figure 8). This allows Minion to accomplish tasks as efficiently as possible (Table 1).

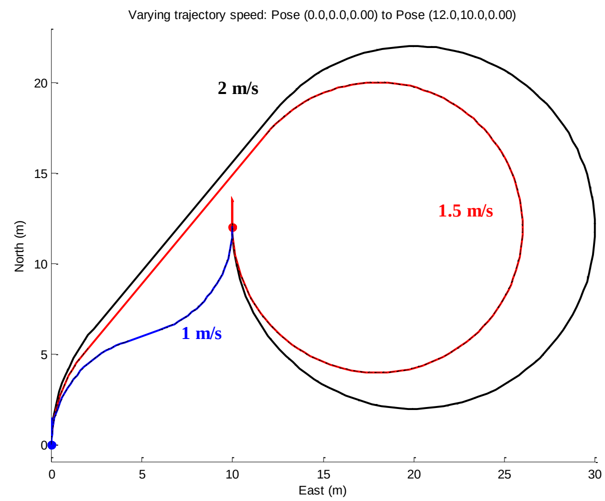

Figure 8 Trajectories at varying velocities

Table 1 Travel times at various operating velocities

Turning radius (m)	Operating speed (m/s)	Path Length (m)	Travel Time (s)
10	2	78.45	39
8	1.5	65.88	44
6	1	16.88	17

The path planner can achieve multiple movement behaviors such as waypoint tracking, loitering, searching, and line hold which are used to generate and follow the paths. In order to generate paths that are obstacle free an iterative approach is taken. First a direct Dubin's path is calculated between the vehicle and the goal. That path is then checked for obstacles, if one is found the earliest intersection is calculated. Four intermediate points around the obstacle as well as two random points are chosen as intermediate goals. The planner calculates the path to each intermediate point, again checking for intersections. This process is repeated until a list of intermediate points with obstacle free paths are found. The planner then steps forward to those points and continues iterating until the goal is reached. Finally the shortest path to the goal is selected as shown in Figure 9.

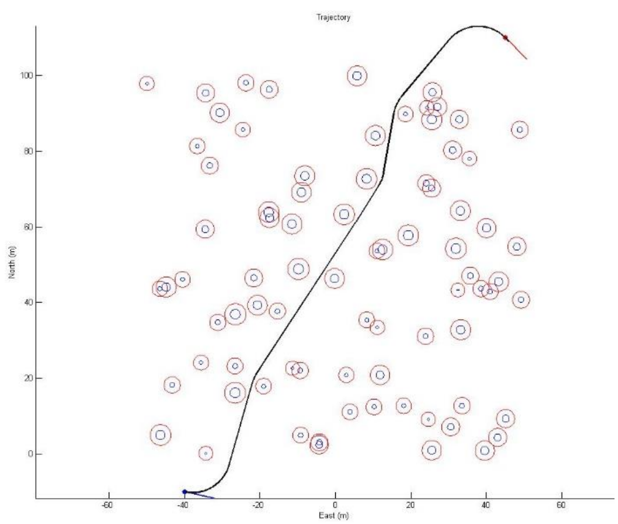

Figure 9 Simulated obstacle avoidance behavior in a cluttered environment with a defined start and end pose

Objective Tracking

Minion implements a multi-modal Objective Tracker with intelligent tasking. Once the user programs the desired objectives and the geo-fence for each task, the tracker begins planning how to achieve each task. The Objective Tracker begins by making guesses at where task objectives are and what will be necessary to accomplish those objectives.

The Objective Tracker will first attempt Task 1, the only task it is unable to skip. It estimates where the start gate is based on the starting waypoint and begins driving toward it. While driving, Minion searches for the gate using Mapper data. Once found, it drives through the gate while estimating where the finish gate should be. Minion then searches for the finish gate, locates it, and drives through it, triggering a transition to Task 2.

During its search for the gates the Objective Tracker uses multiple descriptors of the gates to determine a highest probability match for the location of the gate and the direction in which to go through. Ideally the Mapper would return a location and identification of both the red and green buoys, but the Objective Tracker is capable of operating on more limited information. If two tall buoys are identified in approximately the right location within the geo-fence, the target will be inferred until positive identification is obtained.

The Objective Tracker performs similar deterministic planning for all the other tasks. First it makes a prediction about task objectives, then it confirms with received data, and finally it completes the objectives. While performing this, the run time is monitored to determine when it is best to abandon an objective and move on. Due to the nature of the competition, objectives are always attempted in order.

The Objective Tracker can also use vehicle health data to determine if a task should be aborted or skipped. For example, if the sonar system is not responding during the sonar task the Objective Tracker can decide to end the task early and move on. This allows the Objective Tracker to be very robust to changes in operational capability and environment.

Control

Minion uses a gain scheduled Linear Quadratic Regulator (LQR) control scheme with adaptive disturbance rejection in order to follow trajectories[2]. This allows precise trajectory following while mitigating the effect of waves, currents, and wind. It also gives Minion a large operating envelope in diverse environments.

Disturbance rejection is handled in the global frame while the controller minimizes errors in desired headings and speeds generated by the path planner. Disturbances in the form of winds, waves, and currents experienced by the platform are non-persistent and varying rapidly as viewed by Minion's sensors. However, these disturbances are persistent and slowly varying if viewed from a global frame. In order to estimate and ultimately reject these disturbances an adaptive filter is implemented. The filter uses velocity vector error to determine when a disturbance is present and slowly builds a model of the strength and direction of the disturbance.

Minion is capable of using the disturbance information to help its operation, such as coasting with motors off in a current, tacking in order to be pushed towards its goal, or increasing its operating speed and turn authority to combat adverse conditions. This capability has been tested in currents and winds of up to 5 and 20 knots respectively.

Collaboration

In ERAU's winning proposal, Minion's architecture was designed with a bifurcated sensor system; a cost effective system using existing ERAU owned hardware and a proposed configuration with state-of-the-art sensors. Recognizing the systems engineering aspect of this challenge, ERAU made the decision to further focus on software and sensor fusion, rather than hardware development. To make the proposed state-of-the-art system configuration a reality, the team sought business partnerships with industry leaders for reliable and proven solutions to mitigate challenges posed by the operation and development of an autonomous system.

These partnerships led to product discounts and donations or monetary donations. Many of these business partners agreed to support the project in order to receive feedback on the performance of their products on an autonomous surface vehicle. Examples of these partners include Glenair, APlus Mobile, TORC Robotics, Sparton Electronics, Velodyne Lidar, Torqueedo, RotoTorque Jet, National Instruments, Carlisle Interconnect Technologies and NovAtel all of whose products were incorporated into Minion. Other partners, including the Student Government Association (SGA) at ERAU, Sparton NavEx, Mathworks, and AAI Textron

Systems have contributed to further STEM education.

Securing these partnerships, particularly internationally, required significant time and effort. Additional challenges were encountered as the system changed due to incorporation of new hardware. While ultimately beneficial, the uncertain nature of support caused disruptions to the technical approach and schedule. Ultimately, the team was able to secure enough partnerships to build a state-of-the-art and highly capable system.

Challenges and Solutions

During the development of Minion, multiple challenges were faced. From the outset the compressed time frame of the Maritime RobotX Challenge was a key obstacle. From the proposal being accepted to the competition starting in Singapore is approximately 12 months. For a project of this scope that is a very short period of time. This challenge was overcome by leveraging the experience of the Robotics Association at Embry-Riddle (RAER). This knowledge base was used to ensure Minion was available for testing as quickly as possible and as often as possible.

Technically constructing and operating a large vessel with its sundry support equipment was outside of the experience of the Minion team. Tasks such getting the platform registered with the State of Florida, and operating in crowded waters taught the team a great deal about seamanship. Testing in general was logistically challenging requiring the orchestration of transport to and from the test site for Minion and its chase boat. This in turn required a team of approximately 12 people for testing initially. Although by the end of testing a crew of 5 were able to do the same thing.

Testing

Using the process of complexity through iteration it was decided early on that Minion would have a rigorous testing schedule. This emphasized reliability and system availability. The multiple tests (Figure 10) used to validate Minion and its subsystems was done in a bottom-up manner, meaning simpler base systems such as RC control and the emergency stop systems were tested before more complex systems such as LIDAR classification. During its testing phase Minion was deployed to the Halifax River 31 times totaling over 100 test hours 53 of which were autonomous. Minion was also tested in all manner of weather conditions ranging from 39^{o}F to 107^{o}F, pouring rain, and 20 knot winds.

Figure 10 Minion testing its hydrophone array in the Halifax River

Conclusion

ERAU has successfully developed the Minion ASV platform to compete in the Maritime RobotX Challenge[3]. The system incorporates a novel hardware/software design, modular sensors, and advanced perception and Guidance Navigation and Control algorithms to enable it to complete a variety of maritime autonomous navigation tasks.

During this project the team developed a much deeper understanding of maritime operations and what it takes to develop a platform that is able to be reliably operated in a maritime environment. The scope of the project also required a much higher degree of technical competence and logistical work than anything RAER has previously done.

Future plans for Minion involve using it as a part of a multi-agent autonomous system. Deploying smaller unmanned systems such as aircraft or submersibles to widen its sensor horizon. Missions for such a system include environmental monitoring, wildlife protection and harbor security.

Acknowledgements

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