PropaGator 2015: UF Autonomous Surface Vehicle

Daniel Frank, Andrew Gray, Dr. Eric Schwartz
Machine Intelligence Lab,
University of Florida, U.S.A
email: dzf209@gmail.com
andygrayia@gmail.com
ems@ufl.edu

Abstract—PropaGator 2 is a fully autonomous surface vehicle built to participate in the Association for Unmanned Vehicle Systems International Foundation’s 2015 RoboBoat Competition, held in Virginia Beach, Virginia. This paper describes the hull design, propulsion design, electrical design, software infrastructure, outreach efforts, and the PropaGator team’s approach to completing the challenges presented in the 2015 RoboBoat Competition.

Index Terms—Autonomous Surface Vehicle, Azimuth Thruster, Hubless Propeller, Kort Nozzle, Robot Operating System

I. INTRODUCTION

PropaGator 2 is an autonomous surface vehicle (ASV) designed and built by students in the Machine Intelligence Lab at the University of Florida. This is the third year that the University of Florida will participate in the Association for Unmanned Vehicle Systems International (AUVSI) Foundation’s surface vehicle competition. Last year the team focused on the hull and propulsion system design and developed one of the fastest and most powerful ASVs in the history of the competition, PropaGator 2, shown in Fig. 1. With a sound platform already fabricated, this year the team decided to focus on redesigning the software and control systems of the vehicle. The PropaGator team is comprised of undergraduate and graduate students from the departments of Electrical and Computer Engineering, Mechanical and Aerospace Engineering, and Computer and Information Science and Engineering.

II. MECHANICAL

PropaGator 2 was designed to achieve speeds of at least 10 kts. This influenced many of the mechanical design choices for the platform such as the heavy emphasis placed on the reduction of drag.

A. Hull Design

The upper half of PropaGator 2’s hull was modeled after the M80 Stiletto shown in Fig. 2. The flat planes that make up the features on the top half of the ASV are aesthetically pleasing while also being easy to manufacture. Everything below the waterline was motivated by the goal of achieving 10 kts. For a displacement hull, or a hull that does not plane, hull speed is the theoretical maximum velocity. At hull speed, the ASV becomes trapped behind
its own bow wave and is no longer able to increase its velocity without a significant increase in power. Hull speed is determined by one parameter, its length in the water, using the following equation [1],

$$v_{hull} \approx 1.34 \sqrt{L_{wl}},$$

(1)

where $v_{hull}$ is the hull speed measured in kts and $L_{wl}$ is the length of the waterline measured in ft. Since the competition constrains the ASVs to being no longer than 6 ft, using this formula, the maximum top speed of a displacement boat entry to the RoboBoat Competition can be estimated to be 3.28 kts.

However, the maximum velocity of a planing hull does not depend on its length. The maximum speed of a planing vessel can instead be predicted using Crouch’s formula [2],

$$v_p = \frac{C}{\sqrt{\frac{D}{SHP}}},$$

(2)

where $v_p$ is the maximum planing velocity of the boat measured in kts, $C$ is a constant based on the hull form of the vessel, $D$ is the amount of water the vessel displaces in lbs, and $SHP$ is the shaft horsepower at the propeller. Using this formula, the team determined that it was possible to create a boat that fits within the constraints of the RoboBoat Competition that was able to reach 10 kts. To achieve this, plugs for a planing hull were designed and cut out of EPS foam using a CNC mill. The plugs were then conditioned so that a fiberglass female mold could be created. Once the molds were finished, the ASV was constructed out of fiberglass. By using fiberglass, it was possible to make a strong but lightweight hull.

A catamaran design was chosen over a monohull for several reasons. First, catamarans offer more stability in the roll direction than a traditional monohull. This introduces less noise to the sensors. Second, catamarans are able to displace the same amount of water with a shallower draft compared to a comparable monohull, allowing the ASV to navigate shallow waters safely. Finally, catamarans typically have the advantage of providing less resistance in the water than a comparably sized monohull [3].

The shallow deadrise helps provide a smooth ride to reduce noise for the on-board sensors while still providing a large planing surface to generate lift [4]. Hard chines were added to the side of the hull to give the ASV better forward tracking. The upper style chines help redirect the water from riding up the side of the ASV, which results in a reduction of drag. The V-shape front of the pontoons are designed to help break waves in choppy waters. Once the water is separated, the pontoons have a constant cross section until the stern of the ASV ends with a hard transom. The hard transom allows the water to separate from the ASV at a known point and helps to prevent issues with flow separation.

B. Azimuth Steering System

The team’s previous platform, PropaGator 1, featured four trolling motors that were rotated at set angles of 30° from forward, allowing the ASV three degrees of freedom; translation in two directions and adjustment of heading. While this configuration can achieve instantaneous motion in any direction, the ASV loses efficiency due to the fact that all motions are a result of four thrust vectors with components in opposition. Since boats move primarily in the forward direction, it makes sense to design the ASV to be most efficient when moving
forward. By utilizing two azimuth thrusters, PropaGator 2 is still able to achieve the same mobility as PropaGator 1’s four trolling motors. An azimuth thruster is a marine propeller that can be rotated about the vertical axis to assist in steering. By going from four fixed motors to two steerable motors, the drag caused by the motors was reduced. Additionally, by using steerable motors, PropaGator 2 is more efficient than its predecessor, especially when moving in forward and reverse.

C. Propulsion System

Understanding that once the boat is planing, the thrusters provide the majority of the drag, the team decided to design and manufacture their own propulsion system as shown in Fig. 3. The goal was to minimize drag by shrinking the size or cross-sectional area of the part of the propulsion system that is dragged in the water. Rather than having the motors in the water like the motor pods developed by Hsieh et al. [5] or standard trolling motors, the motors are located inside of the hull. This greatly reduces the size of the propulsion system in the water which in turn reduces drag. The power is transmitted from the motor to the propeller through a timing belt that is attached to the output shaft of the motor and the rim of the propeller. This rim-driven transmission eliminates any drag caused by the hub of a propeller and is discussed in more detail in section II-C2.

One of the major improvements that was made to the propulsion system this year was increased serviceability. Prior to the redesign, the process of swapping out propellers or replacing bearings required 80 min to remove and reassemble the shrouds from both motors. The new shrouds have been designed so that this entire process now only takes a total of 8 min.

1) Kort Nozzle: For safety, the RoboBoat Competition requires all propellers to be shrouded. By designing a propeller that is enclosed by a duct, also known as a Kort nozzle, the team was able to create a duct that helps generate high thrust at low speeds [6] while still producing minimal drag when moving through the water. Ducted-propellers can also help increase fuel efficiency by allowing the ASV to run the propellers at a lower RPM while still maintaining the same velocity as an equivalent ASV with free-propellers [7]. Finally, the ducts prevent prop walk, a phenomena where the stern of the boat tends to strafe in the direction of the propeller’s rotation. Typical twin-screw vessels, boats with a propeller on the starboard and port side, have two different shaped propellers; one propeller rotates clockwise to achieve forward motion and the other propeller creates forward motion by spinning counterclockwise. This balances out the forces that cause prop walk. However, by using the ducted-propellers, only one type of propeller needs to be manufactured which allows for easier replacement if one breaks.

2) Propeller Design: The motivation behind the development of the propulsion system was to reduce drag as much as possible. During simulations and testing, it was determined that the hub in a traditional propeller serves two purposes; providing strength to the blade roots and providing an attachment point for the motor. Consequentially, the hub does not produce any thrust, but it does produce drag.
By going to a rim-driven design, the hub’s only remaining purpose was to provide strength to the blades. Unfortunately, the hub only offers strength to the root of the propeller, which in general, experiences loads that are much lower than those experienced by the tips [8]. By inverting the propeller into a hubless configuration as shown in Fig. 4, the moment arm acting on the propeller tips is reduced, causing an overall reduction of bending moment on the rim-driven propeller compared to an equivalent standard hub-driven one. Additionally, by eliminating the hub, the drag that it produces is also eliminated. The hubless propeller also has the advantage of being resistant to propeller fouling debris [9]. For more information on the theory and mathematics that went into the design of the propellers, see [10].

Once all of the propeller parameters were determined, the team generated a CAD model of the propeller and then cut it out on a 4-axis CNC mill. The propellers were cut out of blocks of polyoxymethylene for its resistance to moisture, long-term fatigue endurance, and high strength and rigidity. The software used to generate the geometry of the blade was a combination of SolidWorks and CAESES Free, a computational fluid dynamics (CFD) integration platform.

Figure 4: Hubless propeller designed and manufactured for PropaGator 2

### D. Final Specifications

A summary of the final specifications of the ASV is listed in Table 1. The maximum speed was recorded from the velocity log of a Yuan 10 Skytraq S1315F-RAW GPS. The maximum thrust was the recorded value from last year’s competition.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Weight</td>
<td>97 lbs</td>
</tr>
<tr>
<td>Dimensions</td>
<td>72 in x 35 in x 21 in</td>
</tr>
<tr>
<td>Max Speed</td>
<td>11 kts</td>
</tr>
<tr>
<td>Max Thrust</td>
<td>56 lbf</td>
</tr>
</tbody>
</table>

### E. Water-Resistant Quadcopter

HUGO is a custom-designed quadcopter manufactured by Aerotestra shown in Fig. 5. With its water-resistant hull, HUGO can operate in inclement weather (light rain) and can land in water. Using four 45 A electronic speed controllers with custom motors, HUGO can fly at speeds up to 30 kts with 8 in diameter propellers. An APM autopilot allows the aircraft to fly autonomously. To control the APM, an ODROID U3 (1.7 GHz quadcore embedded processor) is connected to the autopilot. For vision, a Logitech C920 camera is mounted to a 2-axis gimbal allowing HUGO to “see.” Vision is processed onboard via the ODROID. Communication between PropaGator 2 and HUGO is conducted via a wireless network.

### III. ELECTRICAL

PropaGator 2’s electrical system was designed to support the power requirements of the propulsion system, the computer hardware, and the sensor suite. A combination of commercial off-the-shelf technology and student-developed circuit boards enable operation of the boat. Electrical components are placed in a way to minimize exposure to water and to properly ballast the ASV. Clean and easy-access wire management is achieved through the use of 3D printed parts and removable cable ties.
A. Power Plant

PropaGator 2 utilizes four lithium polymer four-cell batteries to generate an operating voltage of 16.8 V. Each battery has a rating of 6000 mAh for a combined rating of 24000 mAh. The batteries are able to power the ASV for approximately 2 hours. Power from the batteries is passed through a student-designed merge board, which prevents fresh batteries from charging dead batteries. All electrical components are powered by 16.8 V, supplied by the merge board. On average, each motor draws approximately 35 A. PropaGator 2’s main computer is powered by a 220 W power supply. Any sensors not powered by USB from the computer are fed with 12 V supplied by high efficiency switching regulators.

B. Computer and Communications

To ensure that PropaGator 2 has enough processing power, an Intel I7 processor was selected. The operating system was installed onto a solid state drive, ensuring a rapid computer startup. Last year, PropaGator 2 was able to fill an entire 256 GB hard drive with logged data in approximately one hour of run time. This year, the ASV will be outfitted with a 2 TB hard drive, which will allow up to eight hours of data logging.

PropaGator 2 utilizes four wireless routers in bridge mode and is able to have a wireless data rate in excess of 1000 Mbit/s. The four routers are broken into two categories: one master and three bridges. The master acts as the hub upon which all communications will pass through and will be physically located on the shore in a location visible from anywhere on the course. A bridge will be placed on the boat, at the loading dock attached to the competition server, and inside a mobile briefcase. The routers also utilize the less congested 5 GHz frequency spectrum to provide the ASV with more reliable communication.

IV. Sensors and Actuators

A. LIDAR

A SICK LMS111 LIDAR is mounted to the front of the ASV. The LIDAR has a planar sweep of 270°. The laser operates at 50 Hz, providing a range value for every 0.5° of the sweep. The attached servo tilts the LIDAR up and down at approximately 0.5 Hz. Combining the tilting motion with the laser scan, the ASV is able to visualize its environment in three dimensions. Using feedback from the servo and data from the inertial measurement unit (IMU), a graphical user interface allows the team to visualize the 3D LIDAR data that is collected by the ASV as shown in in Fig. 6.

B. Passive Sonar

The ability to track a point source of sound in the water is encapsulated into the passive
sonar pressure vessel. It contains a student-designed passive sonar amplification and filtering board, necessary power regulation, and USB communication. Using four microphones, the hardware is capable of tracking multiple acoustic sources simultaneously provided they are at different frequencies. A Texas Instruments digital signal processor is used to collect the acoustic data, which is then transmitted to the main computer for further processing.

C. Additional Sensors and Actuators

For position determination, PropaGator 2 uses a Sparton AHRS-8 (altitude heading and reference system) and a Yuan 10 Skytraq S1315F-RAW GPS. To visually detect obstacles and challenge objectives, PropaGator 2 utilizes a forward-facing IDS Imaging UI-1240RE camera. Propeller rotation and LIDAR tilting are performed by Dynamixel MX-64T servos. The electronic speed controller used to control the thrusters’ 1200 W Rimfire .60 motors is the Mamba Monster 2 by Castle Creations.

V. SOFTWARE

A. Robot Operating System

The PropaGator team continues to use the Robot Operating System (ROS) for its open source nature and strong community following, which allows for frequent updates and plentiful examples and tutorials. The lab also actively contributes to the ROS open source community. The Machine Intelligence Lab, including teams like PropaGator, has migrated all of its robots to ROS. This makes it easy to write software for one robot and be able to use it on another. This is a powerful tool and was used at last year’s competition when the team used the controller from the lab’s submarine to control the boat. ROS facilitates the unification of software by packaging individual programs into nodes. These nodes are then able to communicate with each other through ROS [11]. The overhead required to allow this communication and any necessary debugging is provided by the ROS environment. ROS also provides 3D visualization tools such as RVIZ, which allow the current states of the ASV’s actuators to be shown on a screen as shown in Fig. 7.

![Figure 7: Sample screenshot of RVIZ](image)

B. Kalman Filter

PropaGator 2 uses an Unscented Kalman Filter [12] to fuse the IMU and GPS modules to determine the pose (position and orientation) of the ASV. Velocity data for the filter is provided by the GPS module.

C. Mission Planner

To give PropaGator 2 a set of ordered and specific tasks, a mission control program was created. The program is a state machine that monitors the status of each task that is running and has timeouts to abort a task if it fails to complete. Preventing one task from consuming the entire run time, the program allocates a measured amount of time to each task. Debugging and monitoring is greatly simplified by utilizing the ROS state machine.
D. Simulator

It is not practical to take the ASV to a body of water every time testing needs to be conducted, thus a simulator was used for testing software for various challenges. A screenshot of the simulated boat performing the navigation test and obstacle avoidance challenges can be seen in Fig. 8. The Virtual Robot Experimentation Platform (VREP) was chosen as the simulator due to its extensive amount of documentation, gradual learning curve, and its compatibility with ROS [13]. The simulator is proving useful in testing software for the interoperability challenge while the team waits for permission from the Federal Aviation Administration (FAA) to fly their quadcopter outside.

Figure 8: Simulated navigation test and obstacle avoidance challenges using VREP

E. Computer Vision

Outfitted with an IDS Imaging UI-1240RE machine vision camera, PropaGator 2 has the ability to “see” the RoboBoat course. In order to reduce the processing load of the computer, the outer edges of the 1080p image are removed. To analyze the images from the camera, OpenCV paired with ROS libraries are used. C++ and Python are the programming languages used for computer vision on the ASV.

F. Controller

PropaGator 2 is an over actuated system, i.e., it has more inputs into the system than it has outputs. The ASV’s outputs consist of its three degrees of freedom; two to describe its planar position on the water and one for its orientation. The four inputs to the system are the two thrust vectors created by two propulsion motors and the two thruster orientations from each steering servo. Due to the over actuation, given a desired trajectory, there may be an infinite number of actuator configuration solutions. To solve this issue, the ASV uses a small network of systems to control its location.

The control system consists of a trajectory generator, a controller to convert those trajectories into a wrench, and a thruster mapper to turn that wrench into the final thrust vectors that we assign to the motors. A wrench is simply a representation of a force and moment acting on a rigid body. The thruster mapping is solved using a non-linear cost function to avoid thrust configurations that would render the boat momentarily unstable. This component is only responsible for solving for a given wrench to fit the dynamics of the ASV. It can generate many thruster configurations and chooses the optimal one based on a cost function that minimizes motor effort. The thruster mapper receives its commands from a main controller that is responsible for verifying with the GPS that the ASV is moving in the direction that the trajectory generator is commanding, as well as generating the wrench that will keep the ASV moving in that direction. Once the ASV has reached the final waypoint of the trajectory generator, it begins station holding until another command is given.

VI. Mission Tasks

This section summarizes the PropaGator team’s approaches to each of the competition’s challenges.

A. Navigation Test

PropaGator 2 will utilize the Point Cloud Library to identify the gates and their locations
by looking for clusters of LIDAR points situated in a round pattern and returning the estimated center of the circle they compose. When the ASV is oriented properly to the gates, a “move forward” command will be passed to the controller which attempts to follow a straight line forward as defined by the ASV’s orientation when the command was sent. As a redundancy, the ASV will also utilize OpenCV to threshold the image by color and size to detect the location of the gates.

B. Obstacle Avoidance

PropaGator 2 will navigate to just outside the entrances of the obstacle avoidance field using its GPS. Once there, it will contact the competition’s network to determine which gates it needs to enter and exit. Using a combination of LIDAR and vision data, it will navigate through the correct gate. The path planner will plan the shortest path from that location to the exit gate. If the ASV detects an obstacle buoy while on this path using its LIDAR and camera, it will react and navigate away from the buoy. Once it is cleared of this buoy, it will calculate a new path to the GPS exit gate.

C. Automated Docking

To accomplish the docking mission, PropaGator 2 will first maneuver to the coordinates of the docking challenge and query the RoboBoat server. Using the camera, the ASV will run a vision algorithm to identify and recognize the three signs as shown in Fig. 9. Next, the boat will place the first desired sign into the center of the camera frame and proceed forward until contact with the pier is made. The ASV will then back away from the pier and return to the original coordinates of the challenge and repeat the approach process for the second desired sign.

D. Pinger Location

For the Pinger Location challenge, PropaGator 2 will use a servo motor to deploy its passive sonar system which was described in IV-B. Listening for a specific frequency, the sonar is able to determine an inclination and declination from the ASV to the source of the sound. Using this information, the ASV will navigate to within a predetermined distance of the pinger and identify the associated buoy’s color. While reporting the buoy’s color and location back to the shore, it will use vision and the sonar to drive around the buoy as a visual indication that it has found the pinging buoy.

E. Interoperability Challenge

For this challenge, the ASV will first use its GPS to navigate to the approximate location of the challenge station. Using the LIDAR and camera, the ASV will detect and navigate to the white buoy and begin station holding. Next, the ASV will then send a signal to the quadcopter via WiFi to begin its mission. The quadcopter will use its own GPS to fly over the sign on the shore. Once there, the quadcopter will send an image over the WiFi network for the ASV to analyze.

As the ASV processes the image and sends its results to the competition’s network, the quadcopter will listen for the ASV’s GPS coordinates, also being broadcast on the WiFi network. The quadcopter will fly to this coordinate, putting the aircraft close enough to the ASV that its camera will be able to find a target
mounted to the top of the ASV. The quadcopter will use this target to visually servo itself over the boat and begin to land. During testing, the team has found that once the quadcopter is about two $ft$ above the ASV, the quadcopter becomes too close to the target to track it properly. To solve this issue, the quadcopter will turn off its motors and fall into a net mounted directly on top of the ASV’s target. The team has had success with this approach in both the VREP simulation as well with actual aircraft [14].

VII. Outreach

The PropaGator team understands the tremendous opportunity that they’ve been given by being able to participate in the RoboBoat Competition, and they feel a responsibility to help pay-it-forward by providing similar opportunities to the next generation of engineers. In addition to engaging in local outreach activities such as engineering museum nights, devoting over 200 hours mentoring a high school robotics team to the world championships, and volunteering to be tour guides for AUVSI Foundation’s RoboTour at the AUVSI’s Unmanned Systems conference, the team has also reached out to several Native American communities where opportunities and resources for education in science, technology, engineering, and mathematics (STEM) are scarce.

A. Navajo Nation

In May of 2014, a member of the PropaGator team was able to visit six schools, perform over 30 workshops on engineering and robotics, and worked with over 1000 students from the Navajo Nation in northeastern Arizona (AZ). The team also helped found and mentor two FIRST Lego League (FLL) robotics teams. Last November, one of the teams, Electro Mutton Nation (EMN), won the Judges Award as well as the award for the best coach/mentor at an FLL tournament in Winslow, AZ [15]. Although EMN was only able to complete four of the 14 missions at their competition, they continue to meet regularly so that they can complete all of the missions before the next season. They have also raised over $700 selling pickles to aid in the sustainability of their team as well as starting a second team at their school.

This past May, the PropaGator team organized the first Navajo STEM Gathering at EMN’s school. Teachers, school administration, and members of the Navajo Nation Department of Diné Education met with institutions such as Northern Arizona University, the University of Arizona, Diné College, Navajo Technical University, Tufts University, and the University of Florida. People traveled over 12,000 miles to the heart of the reservation to discuss the difficulties teachers face while trying to teach STEM on the reservation, the role STEM education should play for the Navajo students, and how all of these universities could help the community meet that role. There were a lot of positive outcomes from this meeting, and there are already plans to meet again at the end of July 2015.

B. Citizen Potawatomi Nation

At the conclusion of the 2014 RoboBoat Competition, all of the teams were awarded five SeaPerch robotic submarine kits to assist them in their outreach efforts. As soon as the PropaGator team arrived back in Florida, they reached out to the Citizen Potawatomi Nation (CPN) in Oklahoma (OK) and helped coordinate for their students to receive these kits to help aid in the CPN’s push for STEM education, shown in Fig. 10 [16].

It didn’t take long for the neighboring tribes to hear about the about the CPN’s robotic submarines and they wanted to know how they could get their own. So the PropaGator team reached out to all of the other RoboBoat teams. The other teams were told that if they weren’t sure with what to do with their kits, there would be a good home waiting for them with the tribes in OK. Georgia Tech (GT) became a partner in this program by donating some of their kits to the tribes of OK. The goal is once
Figure 10: Students from the CPN excitedly build their SeaPerch kits

the students of the CPN become proficient in assembling and using their kits, they will invite neighboring tribes to their build area. The CPN will show the students from the other tribes how to assemble the kits from GT and will then present them as a gift to their guests. In this way, the STEM outreach is further extended and positive inter-tribal relationships are formed between the students.

VIII. CONCLUSION

With a proven hull and propulsion system already implemented, this year the team decided to focus on refining the software and control systems for the ASV. Since last year’s competition, the team has logged over 100 hours of testing time in a local lake that emulates similar conditions to the lake at the competition. The PropaGator team is excited to once again make waves at the AUVSI Foundation’s 8th Annual International RoboBoat Competition.

IX. ACKNOWLEDGMENTS

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The latest PropaGator developments can be found at our web page www.propagator.org.

REFERENCES