Roboboat 2022: Technical Design Report

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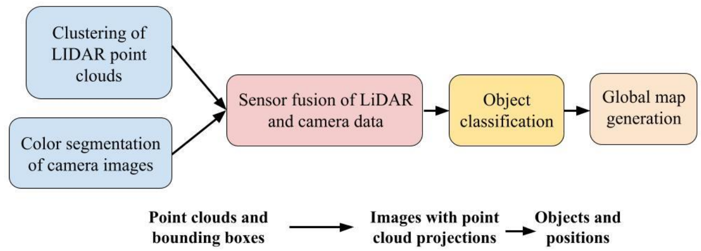
I. Abstract

Arcturus is a brand-new RoboBoat team representing the Massachusetts Institute of Technology. This technical design report explains the design of the autonomous surface vehicle (ASV) built for RoboBoat 2022. After reviewing the scoring and tasks of previous years, the team has decided to attempt every task to maximize our upper limit for point accumulation and give many opportunities for partial credit. Our strategy to achieve all tasks was to design a robust simulation platform, a stable yet maneuverable hull design, and a water gun/skeeball launcher which performs consistently with our autonomous programming.

II. Competition Strategy

A. *General Perception and Task Selection*

Our perception system is used to detect and track course objects through all stages of our runs. For each course object we store our estimate of its most recent GPS position, its type (e.g. red buoy, green buoy, purple frame) and, in some cases, a guess of the task it belongs to. The data from our sensor suite, which is described in more detail in our design creativity section, is processed by our perception system at a rate of about 16 Hz. Using color segmentation and clustering algorithms combined with LiDAR data, we identify buoys, markers, and other course objects in the field of view of our cameras. Any objects detected by our LiDAR but not seen by our camera are labeled as unidentified. These objects are then merged with our global map to either update the position of objects currently on it or to add new objects. We use a Kalman filter on an object's pose to help remove noise and keep positions more stable.



Overview of our perception system

B. *Navigation Tasks*

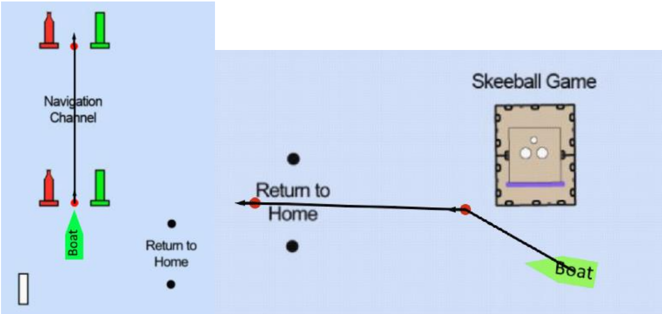
We use the waypoint following feature of the Pixhawk PX4 flight controller, which allows us to send local pose setpoints to our boat. We chose to use this feature because it was simple to use and greatly reduced the complexity of our control system, allowing us to focus on path planning and decision making of our boat.

Using our waypoint system, we only need to generate a series of waypoints that our boat can follow to complete each task. For computing waypoints, we have two phases: global planning and local planning. For global planning, we use various algorithms described below to compute primary waypoints to get through the task. For local planning, we combine the global plan with our sensor data to determine if our global plan is going to collide with any obstacles. If so, we modify our waypoints to move around these obstacles. The output of the local planner is then sent to the Pixhawk flight controller, which controls our actuators to bring us to the desired pose.

C. *Global Planning*

Navigation Channel and Task 6: Return to Home

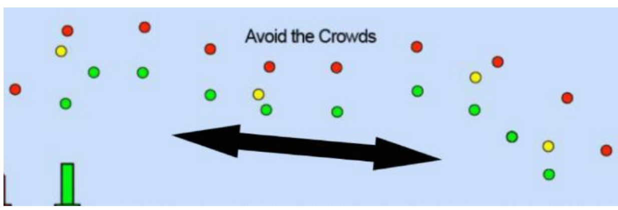
For simple tasks, we use the midpoint of pairs of buoys as waypoints to create simple paths.



Navigation channel paths (left) and “Return to Home” paths (right)

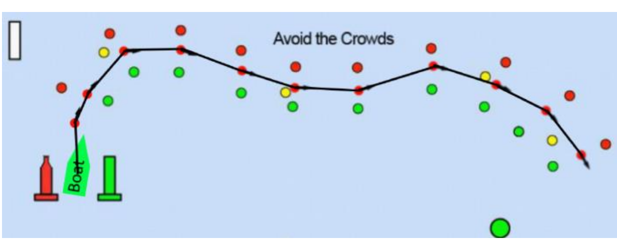
Task 1: Avoid the Crowds

To determine the ordering of the buoys by running principal component analysis (PCA) on their locations. This helps identify which direction the course is going, allowing us to order the buoys.



The direction vector that results from running PCA on the preliminary qualifying course

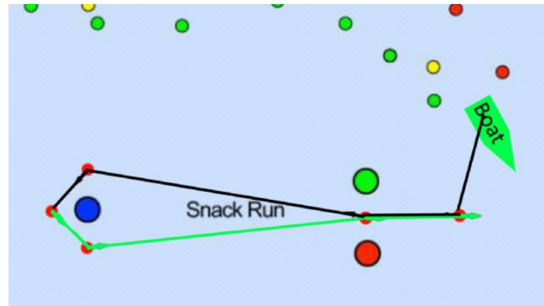
Then, we generate waypoints going through each pair of buoys. The yellow obstacle buoys are not accounted for in our global plan of the obstacle course. Instead, they will be avoided through the local planner’s collision avoidance as described below.



“Avoid the Crowd” path for preliminary qualifying course

Task 3: Snack Run!

To complete this task, the sensor suite attempts to detect the positions of all three buoys. If the marker buoy is not visible or recognized due to sensor limits, its position is estimated as 50 ft beyond the red and green buoys. While this estimate may be inaccurate, our sensor suite should locate the actual buoy while moving towards the estimate, allowing us to refine our path.

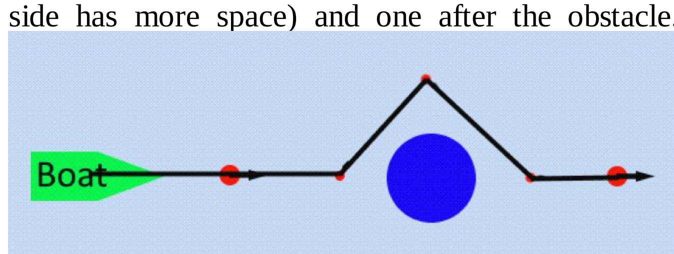


“Snack Run!” path for preliminary qualifying course. Black arrows/lines represent the forward path while green arrows/lines represent the reverse path

D. *Local Planning*

When going between waypoints generated by our global plan, the path from the current position to the waypoint may run into an obstacle such as those in the Avoid the Crowd task. Since obstacles such as buoys can drift over time, it is not ideal to constantly have to update our global path with the position of every obstacle as they move. Instead, we separate collision avoidance from our global path planner and put it into a separate process known as the local planner.

The local planner takes in the output of the sensor suite, our current position, and the current waypoint. Using this, it determines whether a collision will occur along this path, and if it does, it tries to inject intermediate points into this path to avoid the obstacle. First, the local planner searches to the port and starboard of the obstacle to find a clear space for the boat to pass through. Once this is located, the local planner injects 3 waypoints: one right before the obstacle, one to the side of the obstacle (whichever side has more space) and one after the obstacle.



An example of how the local planner adds extra waypoints around an object

E. *Skeeball Task*

Our major goal for this task was being able to independently adjust the horizontal and vertical output of the launching mechanism without moving the entire boat. To do this, we mounted the entire launch system onto a rotating platform to aim in the x and y plane. We also designed the launcher to shoot through a tube that can rotate up and down for control in the z-axis.

F. *Water Gun Task*

Our strategy was to continuously shoot as much water as possible to increase the likelihood of hitting the target and decrease the time it takes to fill the tube. Using the distance, we need to launch and the amount of water that is necessary to fill up the tubes, we were able to calculate the necessary PSI and GPM of 15 PSI and 0.82 GPM respectively. To be safe, we eventually chose a pump with 5.5 GPM and 70 PSI while only contributing 6.65 pounds to our final weight.

Just like our skeeball mechanism, we wanted to be able to aim the water gun independently without moving the entire boat. We accomplished this by attaching the output of the pump to a platform that rotates in the x and y plane and adjusting the power to the pump to vary the z height.

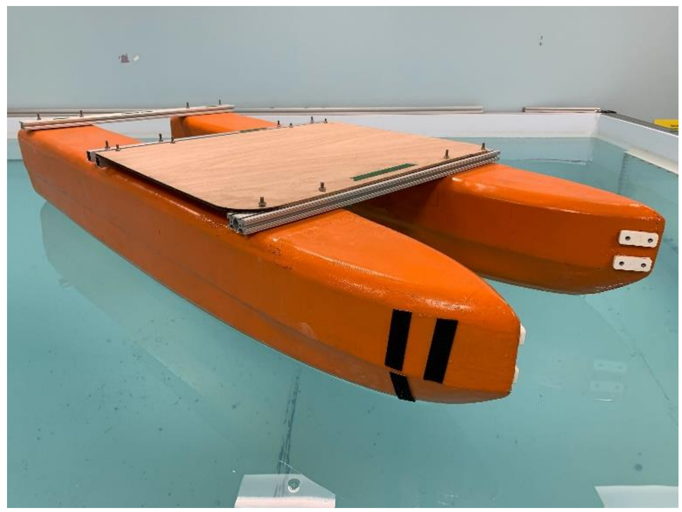
We knew our design would require four degrees of freedom to shoot accurately even when the boat is disturbed, so we created two different aiming prototypes: a robotic arm made of linkages, and two sets of rotating plates that would be connected to the end of the pump. After testing our prototypes, we chose the plates since they were more consistent. Using two waterproof servos, this design would allow us to manipulate the yaw and pitch of the end of the tubing where the water would exit.

III. Design Creativity

A. *Hull Design*

With long-term reusability in mind, we decided to create a vessel which can also serve as a testing platform for future projects. As a result, we decided to go with a 5 ¾' catamaran with a bridge that spans nearly the entire area, to give more flexibility for component placement.

Our marine plywood deck is supported by an aluminum beam structure that also secures the two hulls to each other. The hulls themselves are made of six layers of rigid foam board cut to shape, wrapped in fiberglass, and sealed together using epoxy resin. The joints between the aluminum-reinforced bridge and hulls consist of 3-inch steel studs screwed into small wooden planks embedded underneath the epoxy and fiberglass layers of the hulls. In order to further brace the hulls, we added a carbon fiber undercarriage to increase their strength without adding too much weight. In total, our hulls equipped with electronics weigh 49 pounds and can hold a maximum load upwards of 300 pounds.



Hulls and deck in our test tank

B. *Propulsion*

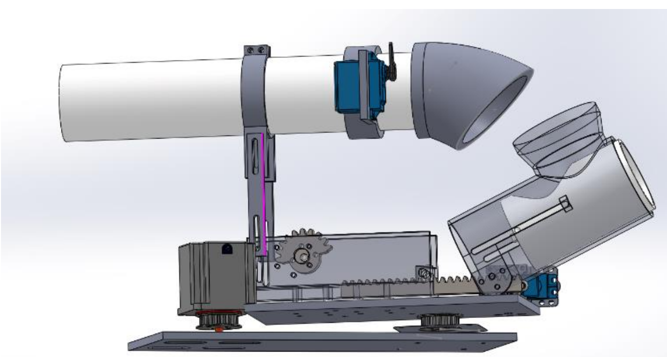
We use two Blue Robotics T200 Thrusters at each hull's stern. To increase our maneuverability, and prevent us from drifting into obstacles, we developed an azimuth thruster pod design which allows us to engage our thrusters in any direction that best suits the situation. The T200 thruster is attached to the servo through a PVC pipe allowing us to reorient the thruster relative to the hull. The system is also mounted to a linear sliding mechanism to allow us to lift the thruster into the hull during transport and deploy the thrusters in the water.

C. *Sensor Suite*

Our sensor suite consists of two stereo cameras, a ZED 2 and 2i, a Velodyne LiDAR, GPS RTK system, and power monitor. Our stereo cameras are arranged to give us an almost 240 degree FOV, each provides an 120 degree FOV, and our LiDAR has a range of about 100 meters.

D. *Skeeball Shooter*

After prototyping several designs [1], we settled on a a spring-loaded system which uses a pinion gear with missing teeth and a rack gear that is connected to the ball holder and extension springs. The pinion gear engages the rack gear to extend the springs and once the gear rotates enough to disengage the rack, the springs pull the ball holder forwards launching the squash ball. We found the system to be very reliable as the system only required the springs to maintain the same pulling force and the rack to be pulled the same distance every time. As long as the amount of force used to pull back the spring is far below (being defined as a safety factor of about two) the stress for deformation of the springs constant will remain consistent enough for our purposes. After testing, we ensured the rack always goes back to the same initial position and the pinion gear and rack do not disengage early or skip teeth to prevent failure or premature launch.



Solidworks design of skeeball shooter

IV. Experimental Results

A. *In-Water Testing*

The Sea Grant Lab, where we are based, has a 13'2" x 9'10"x5' water tank where our boat can cruise about 2-3 feet. This allowed us to test if our azimuth thruster design worked in the water as soon as we finished it. The boat can move forward and backward while turning, as well as turn in place. The boat can also move at speeds going up to 2 meters per second. Even though the boat works in the tank, the lab is a controlled environment, so after some planning we took our boat to the Charles river which is located adjacent to MIT. Our azimuth thruster design once again proved to be successful at turning our boat while cruising as well as when stationary. The boat is able to cruise large distances, however, we only tested on the edge of the river where current is slow.

B. *Battery Testing*

While testing both in the water tank and the river, we used a single 11.1 Volt, 5.1 Amp-Hour lithium polymer battery as our only source of energy to power the boat. This battery supplied enough power to the boat for our testing in the lab and for 30 minutes of cruising in the low-current area of the Charles river. As a result, we are going to be separating our power sources for the thrusters and the rest of our electronics and mechanisms. The thrusters will have sole access to a 22.2 Volt, 21 Amp-Hour lithium polymer battery and we will utilize the 11.1 Volt, 5.1 Amp-Hour batteries to power all other electronic components. We have yet to implement the skeeball and water shooting mechanisms onto the boat, however, we do not expect these to consume enough energy for it to be of concern with our adjusted power distribution.

C. *Sensor Testing*

We've successfully tested our camera system using our test vehicle and can detect colored buoys in the water. Our next step will be real-world testing of our LiDAR sensor and clustering algorithms.

D. *Simulation*

We're currently developing a simulation environment to supplement our real-world testing as well as provide a framework for evaluating our software. Our environment runs in Gazebo Classic, a popular tool for robotics in both industry and academia. Our boat model came from our Solidworks CAD and was converted to the Unified Robot Description Format (URDF) format suitable for Gazebo using in blender using Phobos, a plugin for URDF conversion. Models of the course objects were also created using a combination of blender, Solidworks, and Fusion 360. We use open source plugins to simulate our flight controller, sensor suite, and propulsion system.

Acknowledgments

We want to thank all of the sponsors whose generosity allowed us to not only build our boat, but also foster a space where students can learn and grow together.

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- MIT Edgerton Center
- RoboSys
- ProjX
- Baker Foundation

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None of this would be possible if we were not given space and training to access the machine shops and makerspaces around MIT.

- MIT Sea Grant
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- MIT Laboratory for Manufacturing and Productivity
- N51 Edgerton Center Team Shop
- 4-409 Edgerton Student Project Laboratory

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- Tolga Durak
- Paul Cheek

REFERENCES

[1] "Kramayer ve Düz Dişli Rack and Pinion," GrabCAD, 23-Jan-2016. [Online]. Available: https://grabcad.com/library/kramayer-ve-duz-disli-rack-and-pinion-1. [Accessed: 03-Mar-2022].

[2] Kalman, R. (1960) A New Approach to Linear Filtering and Prediction Problems. ASME Journal of Basic Engineering, 82, 35-45. http://dx.doi.org/10.1115/1.3662552

[3] Karl Pearson F.R.S., "LIII. On lines and planes of closest fit to systems of points in space," The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, vol. 2, no. 11, pp. 559–572, 1901, doi: 10.1080/14786440109462720.

APPENDIX A: COMPONENT SPECIFICATIONS

Component	**Vendor**	**Model/Type**	**Specs**	**Custom/Purchased**	**Cost**	**Year of Purchase**
LiDAR	Velodyne	HDL-32E	80-100m, +/- 2 cm accuracy, 360 Horizontal FOV, +10 to -30 Vertical FOV	Borrowed	$4,000	2022
GPS	Reach	M+ RTK GNSS Module	GPS, GLONASS, BeiDou, Galileo, QZSS and SBAS, 8km range,	Donated	$265	2022
IMU	Adafruit	BnO055	9-DOF	Donated	$30	2021

Motor Controller	PX4	Pixhawk 4	Interfaces: • 8-16 PWM outputs (8 from IO, 8 from FMU) • 3 dedicated PWM/Capture inputs on FMU • Dedicated R/C input for CPPM • Dedicated R/C input for Spektrum / DSM and S.Bus with analog / PWM RSSI input • Dedicated S.Bus servo output • 5 general purpose serial ports • 3 I2C ports • 4 SPI buses • Up to 2 CANBuses for dual CAN with serial ESC • Analog inputs for voltage / current of 2 batteries	Donated	$90	2021
Camera 1	ZED	ZED 2	120 FOV, Built-in IMU barometer, magnetometer, positional tracking, spatial object detection, neural depth sensing	Borrowed	$449	Unknown
Camera 2	ZED	ZED 2i	Above, IP66-rated	Purchased	$549	2022
Computer	Intel	NUC Kit NUC7i7DNHE	8th gen Intel Core Processors, Ubuntu 18.04, 1.90 GHz processor base frequency	Borrowed	$1,199.00	Unknown
Servo	Hi-Tec	HS-646WP	Speed (Second @ 60°) 0.20 ~ 0.18 Maximum Torque Range oz. / in. 157 ~ 179	Borrowed	$50	Unknown
DC Motor	Andymark	NeveRest Classic 60 Gearmotor	Maximum Power: 14 Watts No Load RPM: 105 RPM Stall Torque: 525 oz-in	Borrowed	$29.50	Unknown
Stepper Motor	Stepper Online	23HP22-2804S	Number Of Phase: 2 Step Angle: 1.8 deg Holding Torque: 1.26 Nm(178.4oz.in)	Borrowed	$29	Unknown

ASV Hull Adhesive	West Marine	Two Part Epoxy Solution	West System 205-B, 105-B	Donated	$170.00	2021
ASV Hull Filling	Owens Corning	FOAMULAR Unfaced Foam Board Insulation	3-in x 4-ft x 8-ft	Donated	$45.00	2021
ASV Hull Wrap	McMaster-Carr	Fiberglass Wrap	50-in x 15-ft x 0.035-in	Donated	$60.00	2022
ASV Hull Undercarriage Reinforcement	McMaster-Carr	Carbon Fiber Wrap	Unidirectional Weave, 50-in x 36-in x 0.014-in	Donated	$67.49	2021
ASV Hull Platform	McMaster-Carr	Marine Grade Pressure-treated Plywood	1/4-in x 2-ft x 4-ft	Donated	$88.80	2022
Propulsion	Blue Robotics	T200 Thruster and Basic ESC	Full Throttle FWD/REV Thrust @ Maximum (20 V): 6.7 / 5.05 kg f Operating Voltage: 7-20V Full Throttle Current @ Maximum (20 V): 32A Full Throttle Power @ Maximum (20 V): 645W	Borrowed	$236.00	2021
Battery (11.1V)	Venom	Professional DRONE Series LiPo Battery	8C 5100mAh 11.1V	Borrowed	$50.00	2021
Battery (22.2V)	Ultra Power	LiPo Battery	30C 21000mAh 22.2V	Borrowed	$250.00	2017
Waterproof Connectors	CGELE	Cable Gland Waterproof Adjustable Connectors	PG7, PG9	Purchased	$15.00	2021