UM::Autonomy's Daedalus and Icarus

UM::Autonomy 2019 RoboNation RoboBoat Competition Final Paper

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Abstract

This paper describes the development process and competition strategy of Daedalus and Icarus, the University of Michigan's boat and drone submission for the 2019 RoboNation RoboBoat competition.

Introduction

UM::Autonomy is the University of Michigan's Autonomous boat engineering build team. This is the 13th time UM::Autonomy has participated in the RoboNation RoboBoat competition. However, this year's team oversaw the single largest year over year change in the team's history. Encompassing team management strategy, design conventions, breadth of challenges attempted and quantity of new hardware and materials utilized in our design. The culmination of these changes has resulted in a dramatic improvement over previous years' designs. Most importantly, these enormous changes have fostered a more creative environment for our team's members and developed greater continuity in our approach to solving the challenges that exist within the RoboBoat competition. We are excited to present our process and the results of our work in this paper.

Design Creativity

Team Development

While the goal of competition is to win and showcase the capabilities of Michigan engineering, our team serves as an environment to develop our members and expose them to opportunities and fields of research that would otherwise not be accessible until late in their college careers or beyond. As a result, we wanted the core focus of this year to be on developing a team structure that was conducive to team member growth and sustainability of the organization as a whole.

Figure 1: Actively Recruiting Future Teammates

We accomplished this by actively engaging potential new members from all schools within the University of Michigan and constantly asking for feedback in order to provide opportunities that best matched members' interests.

Comprehensive Design Approach

In years past, one of the largest detriments to the success of our team has been an isolated approach to the design of our complete system. As a result, this year we focused an entire position within the team's officer core on systems engineering. The intention was that at every step of the design process all other subteams would be aware of the decisions being made and the rationale for those decisions. This created a more cohesive development process and streamlined approach to creating design constraints and sub task completion strategy.

Hull Design

The University of Michigan is one of the few schools in the United States with a Naval Architecture and Marine Engineering Department. In addition, the proximity and close relationship between the University and the automotive industry results in an engineering ecosystem where our team could pursue greater complexity in our hull design while minimizing cost associated with development and fabrication.

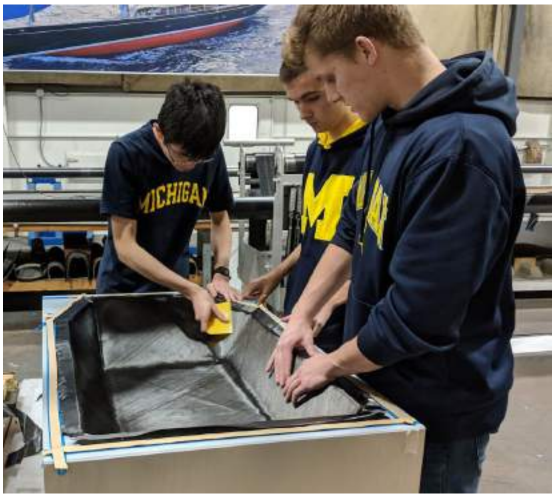


Figure 2: Laying up Carbon Fiber for Autoclaving

Based on lessons learned from previous design iterations of the boat, our design objectives were to reduce weight and size, increase stability, optimize sensor placement and utilization while also increasing modularity and durability.

Our boat, “Daedalus,” achieved these goals. Much lighter and more longitudinally stable than previous iterations, Daedalus maintains an open deck layout with our internal electrical box placement and deck mounted sensor suite. This design allows for easy modification of hardware and rapid design interactions.

This year marked our team’s transition from using fiberglass to carbon fiber for our boat’s hull. This drastically reduced our boat’s overall weight and fabrication time. Ultimately, the core hull of the boat had an overall weight reduction from last year’s 75 Lbs fiberglass and aluminum hull to a carbon fiber shell weighing just 5 Lbs, 6 ounces. In addition, this year our team expanded our use of 3D printing, investing in our own printer and using it to produce all of our boat’s sensor mounts.

Drone Design

To complete this year’s interoperability challenge, we have designed a drone from the ground up. The drone uses a custom built frame, square carbon fiber tubing cross sections and CNC milled carbon fiber plates as the core structure. The custom frame is much more rigid than any stock frames on the market, reducing vibration and producing a smoother video feed. Our drone also houses the necessary hardware required for autonomous landing and onboard computer vision. A circular section of foam is attached to the frame below the lowest sensor to provide buoyancy, as well as a mating surface between the drone and the landing pad on the boat. The landing pad has a circular V channel to guide the drone to its correct position on the landing pad and allow for a greater margin of error during IR-Lock assisted autonomous landing.

One of our biggest concerns in the design of a multivehicle system was communication latency. Our solution to this problem was to design two highly isolated systems. The intention being that the drone can operate with almost no information from the boat. The small communication layer necessary a carried out by the lightweight MAVLink serial protocol. Most of the computer vision and logic processing necessary for autonomous operation of the drone is carried out by our onboard companion computer, an ODroid-XU4. The companion computer sends control commands to the flight controller over a wired serial connection, allowing for low latency and stable control, creating a highly self-sufficient system.

Hydrophones for Time of Arrival (ToA)

Our boat uses a system of four hydrophones to perform Digital Signal Processing (DSP) on the pulse emitted during the Automated Docking challenge. We ultimately settled upon using a custom Printed Circuit Board (PCB) with an onboard DSP chip. Our system relies on ToA, where by measuring the time difference between the arrival of the pulse at any combination two hydrophones, we can calculate the Direction of Arrival (DoA) of the pulse and its distance from the center of the hydrophone array.

Figure 3: UM::Autonomy Hydrophone Array

Navigation

In the past, our boat took a very naive approach to navigation: travel in a straight path while avoiding obstacles as they come close. While this may work for simpler challenges, it fails in situations with many obstacles and "hidden" target locations. This year, we decided to make a more "intelligent" system that plans a path to our destination ahead of time while factoring in things like obstacle avoidance, drift, and more.

We achieved our goal by using a costmap, or weighted occupancy grid. With this, traditional graph theory algorithms for traversing weighted graphs can be used. We chose to use the A* path planning algorithm because its reliability and ease of implementation. This algorithm ensures the generated path avoids obstacles and generally ensures optimality. To help the algorithm work better with the boat's movement model (the boat can't very sharp turns well and it drifts), the provided map is re-weighted based on the location of obstacles and the boat's current orientation. Weighting around obstacles will give the boat a bit of free room for drifting when moving around obstacles. Weighting based on orientation helps ensure the chosen paths are realistic for the boat to follow, rather than expecting it to turn 180° when already moving forward. Once we generate a path, as we travel it, we verify that the chosen path remains valid as the boat moves, and make changes if needed.

Core Subsystems

Electrical System

Modularity and Ease of Use

One key characteristic we wanted for the electrical system this year was modularity of the electrical box. By using a waterproof case as the housing for the majority of our electrical system, we decided to implement easy disconnect connectors on the outside of the electrical box. These connectors aided in the removal of the box from the other electronics mounted to the hull of the boat. With easy removal of the electrical box, the repairability and ease of testing of the electrical system dramatically increased. For example, the AI team or Electrical team can take the electrical box and work with the boat's computer or other electronics without the need of the entire boat.

Duplication of Sensor and Contingency Systems

Another implementation we pursued was to have a backup electrical system. With the easy removal of the electrical box, we are able to take one electrical box and replace it with its twin system. This is useful for situations where the electrical box begins to show abnormal behavior, we can quickly replace the box and resume testing. While a large investment of resources, we found having twin boxes offset the cost of lost testing due to electrical failures.

Competition Strategy

This year, because we started with a clean slate, we decided that we wanted to attempt all of the competition's challenges. Because of this ambitious goal, we needed to make a number of design decisions, including system architecture, hardware choices and design, and integrated third-party systems. In the end, the ultimate goal was to design a system that is sufficiently generic and flexible enough to use for any challenge.

Software Stack

When designing the software stack, we decided to break it into two main parts. One part handles generic tasks, such as object detection and navigation, while the other part handles challenge specific logic. Each of these systems needs to interface cleanly with the other during simultaneous operation, a requirement that led to our decision to use ROS (Robot Operating System). ROS not only allows processes to interface with each other, but it also allows them to send feedback and synchronize with each other.

The base system in the software stack consists of the controls, perception, and navigation sub-systems. The controls subsystem interfaces with the sensors, providing sampled and filtered sensor inputs while sometimes fusing sensors together to supply more useful and accurate measurements, like the boat's pose. The controls sub-system also provides a basic interface for moving the boat, translating target locations into thruster signals. The perception sub-system takes in camera and LiDAR data and detects the existence and locations of various objects that may be of importance to the challenge, more specifically spheres, cylinders, and cuboids. These objects are then matched with camera data to provide more useful classifications, such as buoys or docks. The navigation sub-system provides an interface for navigating to a specific goal while abstracting away things like obstacle avoidance and communications with the controls subsystem. This sub-system takes in a map waypoint, the boat's orientation, and a costmap (occupancy grid) and generates as optimal a path to the goal as possible.

The challenge specific logic needed to be well-structured, yet flexible enough to allow for unique or optimized solutions to each challenge. To achieve this, this logic was structured into a scheduler-like system. Each challenge in the competition is assigned or broken into various "tasks", which are queued and executed based on external network input or the boat's state. These tasks, using the base sub-systems as building blocks, contain specialized instructions for various other subsystems of the boat.

Raise-the-Flag: Drone Interoperability

Although our general system philosophy was to promote a high degree of flexibility, the Raise-the-Flag challenge required a specialized system for detection of the desired dock. For this, we use our quadcopter named Icarus.

Because of the high degree of complexity in designing flight software for quadcopters, we decided to utilize an open-source codebase known as ArduPilot, with customized commands running on an onboard companion computer.

Sensors and Landing

In addition to a flight computer, Icarus carries an onboard 4K camera to detect the 7 segment display while flying over the dock, and uses this camera and a GPS system to fly to its destination. Additionally, it syncs its GPS with the system onboard the boat to return for landing. Early in the design process, we determined that landing on a drifting vessel would be one of the most difficult parts of the challenge. As such, we decided to utilize a landing solution known as IR-Lock. With the IR-Lock system, a bright infrared beacon is mounted on the deck of the boat, which is detected by a camera mounted to the drone. The camera then directs the drone to center and land above the beacon. This beacon guides the drone onto a custom landing cone to ensure a safe landing.

Experimental Results

As a team based in Michigan, one of the greatest challenges that we face is finding ways to test the boat throughout the entire school year. With such a long winter, water time is very scarce, and outdoor water time is even more so. This has led to us dividing our boat testing into three different categories: simulated, indoor, and outdoor.

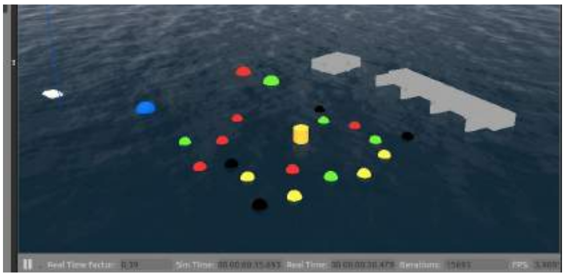
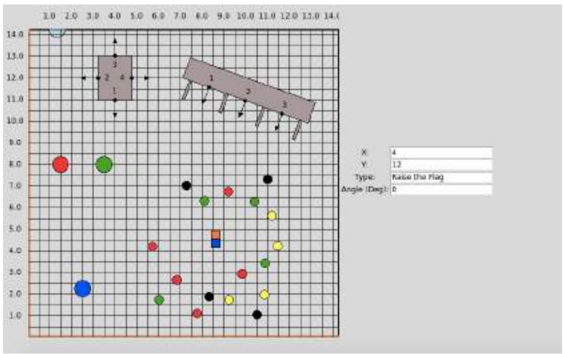


Figure 5: The output of the builder in a Gazebo world file



X: 4
Y: 12
Type: Raise the Flag
Angle (Deg): 0

Figure 6: Our custom made world builder being used to make a competition course

Simulated

Simulated testing is by far our most convenient method of testing. Since it requires no physical component, we are able to utilize the Gazebo simulation suite to test many of our boat's core systems, such as path planning and task planning. Gazebo is also an invaluable tool for integration testing, as it allows us to ensure that all of our software systems are interacting correctly before the boat ever touches water. We use simulation generously to test our systems so we can save time when we're on the water. As of the writing of this paper, we have successfully tested Autonomous Task, Speed Gates, and Find the Path within our simulator.

Indoor Water Testing

While simulation is useful, it starts to lose effectiveness when we need to test how our software interacts with actual hardware devices. In this case, our next best option is to test indoors at the University of Michigan Marine Hydrodynamics Laboratory. The water tank there is narrow and does not get GPS reception. While this limits its utility, it was still invaluable during the winter as it allowed us to test our perception and PID tuning systems months earlier than we normally do.

Outdoor Water Testing

When we are prepared to do a full test of the boat, there is no replacement for open water. This is necessary when we need access to GPS. Thus, the main value of outdoor testing for us was in testing our localization and running integration tests of our path planning and task planning systems with real hardware in the loop.

Figure 7: The boat being tested in the Michigan Marine Hydrodynamics Laboratory

Conclusion

In conclusion, we have accomplished a massive overhaul of nearly every core aspect of our team. Our commitment to communication, a comprehensive design process, improved software stack, and development of an effective UAV are all major strides over last year's improvements. Our improved testing and development cycle have allowed us to refine our system, and we hope to continue to make similarly massive gains moving forward. We are thrilled to compete in the 2019 RoboBoat Competition and are proud of what we as a team have accomplished this year.

Acknowledgments

The success of our team would not be possible without the incredible support of the University of Michigan, our advisors, our committed alumni, and industry sponsors. Among those we would like highlight the tireless support provided by the team at Ford Motor Company and hands-on coaching provided OffShore Spars during the carbon fiber layup process. A special thanks to Professor Kevin Maki for his involvement and mentorship to the team throughout the year.

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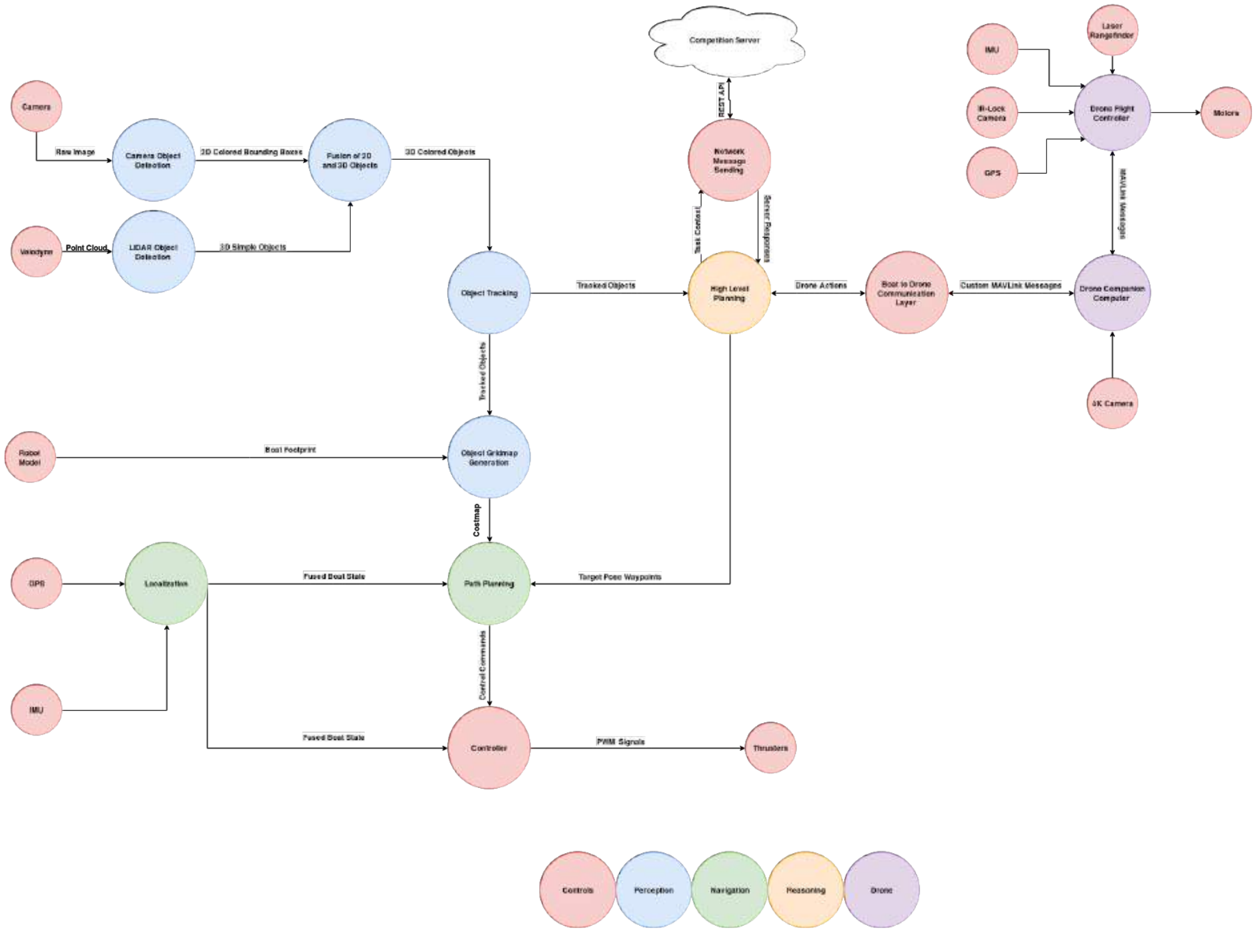
Appendix A: Component Specifications

Component	**Vendor**	**Model/Type**	**Specs**
ASV Hull form/platform	Internal/Ford/OffShore Spars	Custom Monohaul	5 lb, 8 oz Shell
Waterproof Connectors	Souriau	UTS Trim Trio Connectors	IP68/69K
Propulsion	Blue Robotics	T-200	Max Forward Thrust: 11.2 lb
Power System	Custom	M4-ATX	
Motor Controllers	Blue Robotics	BESC30-R3	
CPU	Intel	i7-8700K / i7-8086K	Six-Core, 3.7GHz, 12 MB Cache
Teleoperation	Ubiquiti	RocketM5	5Ghz
Inertial Measurement Unit (IMU)	Sparton	IMU-AHRS 8	Roll/Pitch/Yaw Accuracy: 1° RMS
LiDAR	Velodyne	VLP-16	Accuracy: 3 cm Range: 100 m
Camera	Logitech	C920 HD Webcam	1080p
GPS	Hemisphere	A222	8 mm + 1 ppm with RTK
Hydrophones	Aquarian	H2a	10Hz-100Khz
Aerial Vehicle Platform	Custom	Carbon Fiber	
Motor and Propellers	SunnySky	X2212 980KV Multirotor	930 gf, 12.5 V, 13 A
Power System	Turnigy		
Motor Controllers	Turnigy	MultiStar 40A	
Companion Computer	HardKernel	ODroid-XU4	OctaCore, 2 GHz, 5V/4A
Cameras	e-con Systems	See3CAM_CU135	4K USB
Autopilot	HolyBro	Pixhawk 4	
Flight Controller	ArduPilot	Copter-3.6	
Inter-vehicle communication	Holybro	Telemetry Radio V3	100 mW Serial Mavlink
Team Size	University of Michigan	CS, CE, EE, ME, NAME, BBA	60 Members
Expertise Ratio	Internal		1:4
Testing time: Simulation (Hours)			200
Testing time: Indoor Pool testing (Hours)	Marine Hydrodynamics Lab, Michigan Nadatorium		35
Testing time: Outdoor Pond testing (Hours)	Ann Arbor, MI and Byron Center, MI		75

Appendix B: Software Stack Diagram



Appendix C: Electrical Box Diagram