Qubo V: RoboSub 2024 Technical Report

See Appendix A for the Team Roster

***Abstract*—The Robotics at Maryland (R@M) Team at the University of Maryland dedicated the 2023-2024 academic year to enhancing the reliability and adaptability of their competitive Autonomous Underwater Vehicle (AUV), Qubo, for RoboSub 2024. This was achieved through the improvement of durability in hull design and creative design of the pneumatics system, the redesign of the daughter card system to enhance troubleshooting, and the addition of the smaller AUV 2bo. Moreover, the team streamlined their internal software tools, running a ROS-based software system that allows for flexible execution of competition tasks [3]. With an emphasis on taking the novel approach, these comprehensive advancements enabled Qubo to successfully complete prequalification for RoboSub 2024 and gain a competitive advantage for this year's autonomy challenge.**

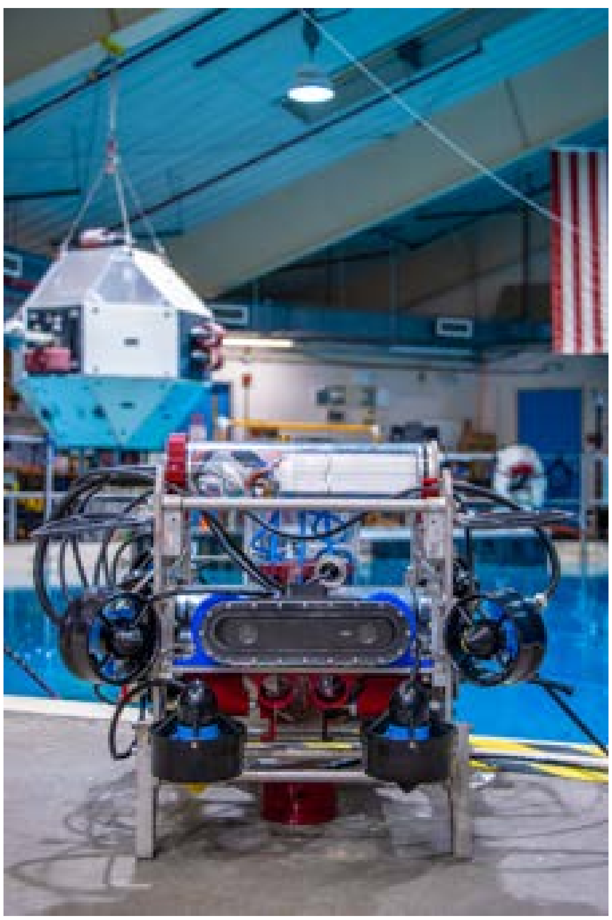

Fig. 1: Qubo by the testing pool.

I. Competition Strategy

A. General Strategy

The team's strategy for the 2024 competition emphasizes an innovative approach, focusing on tasks that are typically less attempted. After last year's competition, the team thoroughly analyzed their performance and that of other teams. A key observation was that the leading teams distinguished themselves by successfully completing at least one end-effector task, despite these tasks being more challenging and requiring extensive testing for reliability. This insight guided the team to streamline system design and enhance vehicle operation, aiming to maximize testing time both before and during the competition. To achieve this, three key criteria were established in the design and planning of Qubo for the 2024 RoboSub competition:

- **Integrated backplane** to streamline maintenance on the hull
- **Stable electronics** with the ability to troubleshoot and locate faults quickly
- **Software behavioral reliability** and ease of operation

By adhering to these principles, the team has optimized Qubo's design to improve its performance and reliability. Emphasizing repairability and adaptability minimized the time required for repairs and enhancements. This efficiency enables full use of practice sessions, ensuring no valuable testing time is lost. Each practice run is used to test and validate various fixes, software optimizations, and adaptations, ensuring that Qubo operates at its best. By maximizing the efficiency of practice runs, the team can focus on mastering more difficult and less frequently attempted tasks. This strategic focus should in theory enable R@M to stand out from other teams and gain a competitive edge that significantly enhances prospects of winning the competition.

B. Course Strategy

The primary objective is to complete the same tasks as last year, namely the buoy collision and the torpedo tasks, while also aiming to exceed previous performance. The team also plans to introduce a smaller mini robosub, named 2bo, which will communicate with Qubo over sonar. Additionally, plans include executing flips and handling the surfacing task with sorting bins.

As the team aims to tackle more complex tasks, the robot design has grown more intricate with the addition of a marker dropper, a claw mechanism, and a pneumatics system to drive it all. This increased complexity brought significant challenges, particularly the issue of wire bulk within the hull. Compressing numerous wires in a confined space risked loosening connectors and damaging boards, all inconveniences that team could not afford. To address this, the team implemented a backplane system to reduce wire bulk, despite knowing it would require substantial time and effort. This has been one of the most notable improvements this year. Additionally, the added challenges of introducing 2bo was balanced by simplifying the software design. Implementing a binary communication system between Qubo and 2bo offset the added complexity with a streamlined, robust software interface. This approach ensures that reliability remains uncompromised while expanding the system's capabilities.

II. Design Strategy

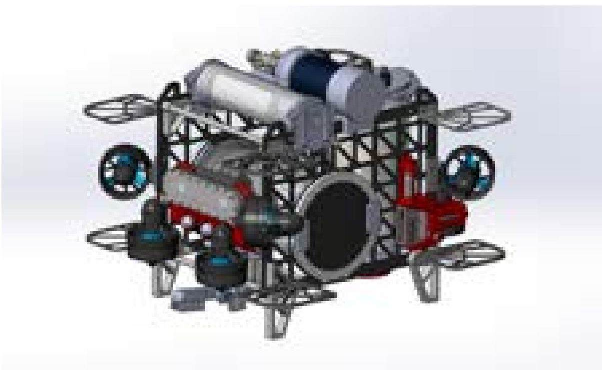

Fig. 2: Rendered CAD model of Qubo.

Last year, the team started the process of cleaning up a barely-functioning robot left from the year prior [1]. This year followed a similar strategy, fixing the things that were questionable in their ability to work, while retaining the parts of the robot that proved to be satisfactory for this year's competition.

A. Pneumatics

The largest mechanical development on Qubo has been the implementation of a custom pneumatics system. Compressed air is regulated from a paintball tank into an enclosure containing 12V solenoid valves. Four of these valves direct air to pistons that produce actuations for Qubo's primary end effectors. Two pistons are used to fire two torpedoes, one to actuate the marker dropper, and one to actuate the claw. Altogether, this system creates a much more reliable method of actuation compared to servos.

The team chose to implement a pneumatics system on the robot for the reason that unreliable servos from the previous year leaked water in the hull, eliminating all end effectors from working in the 2023 competition. This, combined with the fact that rotational motion is less effective than linear motion, suggested that the team look into pistons for much more reliable actuation than servos. After the addition of a more compact DVL, it was ideal to optimize the extra space with a pneumatic system built from scratch by the team to learn the engineering process [4].

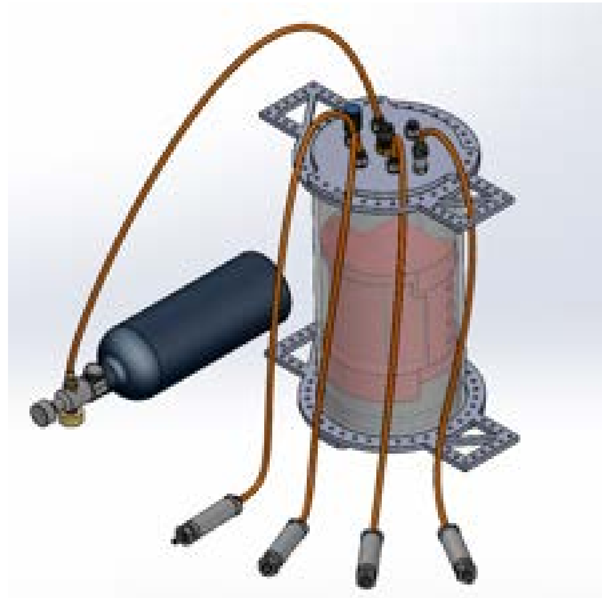

Fig. 3: Rendered CAD model of the pneumatics system.

B. End Effectors

After Qubo's infrastructure took full shape, end effectors, or mechanisms used to help a robot interact with its environment, were designed and implemented. The major end effectors needed for this competition were a two prong claw, an updated torpedo launcher, and a dropper system, which are discussed below.

1) Marker Dropper: The dropper end effector is designed to accomplish a specific task in competition: identifying a bin and dropping a marker into it on the correct color. It is crucial to R@M's competition strategy as it focuses on completing a task historically overlooked by other teams, such as the dropper/marker task. The dropper system was designed around the linear actuation of the pistons to ensure precise marker deployment into the designated bins. This approach simplifies the mechanical design, enhances control, and optimizes speed, making it well-suited for competitive environments where accuracy and performance are critical. Utilizing Qubo's pneumatic piston actuators, the dropper can release one marker per actuation and reload for subsequent uses. It is capable of housing two markers simultaneously, as per competition rules, allowing for two distinct drops. This redundancy ensures that if the first drop is unsuccessful, the second marker is available for a subsequent attempt.

Throughout its development, the dropper underwent several iterations, with design improvements made along the way. The core mechanism remained consistent, with enhancements focused on improving functionality and ease of use.

2) Torpedo Launcher: The self-propelled torpedo project underwent a complete redesign from the previous year, replacing springs with supercapacitors and a motor. Its primary objective is to remain securely held by the robot until released, propelling itself forward in a straight line. This precision addresses the unreliable nature of traditional spring-powered mechanisms directly. Additionally, electric torpedoes are critical to the team's strategy because they can achieve long-distance propulsion, potentially earning an extra 300 points.

The torpedo underwent iterations in size, shape, mechanics, and electronics while maintaining its self-contained design and direct interface with the pneumatic system. The entire torpedo project comprises only five components: barrels that provide grooves for the torpedo and housings for the levers, two levers equipped with magnets to activate the torpedo and prevent it from dislodging, and two piston mounts that connect and actuate the levers. A standout feature of this project is its electrical circuitry, visible through clear resin, which adds to its uniqueness and functionality.

3) Claw System: In order to interact with markers and bins during competition, the team developed a compact claw mechanism. The claw employs a pneumatic piston and a rack and pinion system for opening and closing. Opening the claw involves the piston extending forward, which moves the rack forward, thereby rotating the pinions and opening the claws. Closing the claw reverses this process as the piston retracts. The gripper's role is to securely hold objects grabbed by the claw, achieved using 3D-printed TPU material. The first layer of the gripper includes a groove that fits into the claw mechanism, with screws fastening the gripper and claw together. The second layer features a hexagonal pattern designed to compress under pressure, ensuring a firm grip. The final layer has a simple groove pattern to enhance gripping capability. For mounting and attachment, two brackets securely encase the claw and piston. These brackets are fastened together with screws that thread into heat-set inserts. Hooks on the brackets grip Qubo's lower bars to securely attach the claw mechanism.

C. Electronics Updates & Hull Restructure

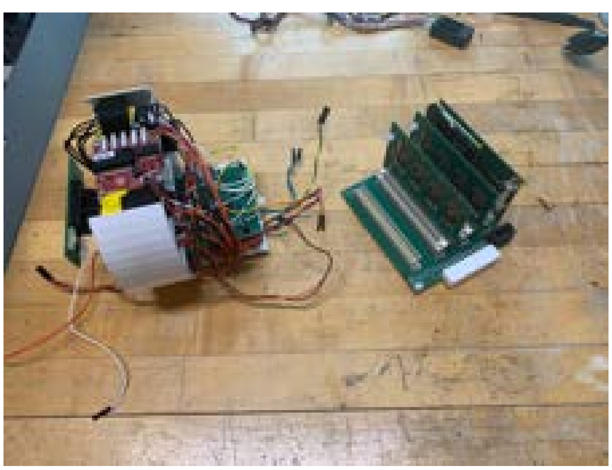

Fig. 4: On the left is the old electrical system from 2023; compare this with the new backplane electrical system on the right.

Last year, Qubo's electrical infrastructure faced significant challenges, including mechanical failures from shipping, fragile assembly processes, and system-wide failures due to a monolithic power/control board. Additionally, transient shorts on the 12V power bus caused damage despite protective measures. This year, the team aimed to solve these issues with a robust design strategy featuring a backplane and daughter card system consisting of dedicated ESC and power cards, all of which enhance reliability, modularity, and protection.

1) Electrical Backplane System: Qubo's new backplane system is a 4-layer PCB designed to host multiple cards using 96-position Eurocard connectors. This system significantly reduces wire bulk inside the hull by 90%, providing a cleaner and more organized setup. The Eurocard connectors were selected for their versatility and robustness, enabling reliable power and signal conduction at a low cost. The modular nature of the backplane allows for easy swapping of cards in case of failure, ensuring minimal downtime and streamlined maintenance.

2) Backplane Daughter Cards: The ESC cards are designed to mount four Electronic Speed Controllers (ESCs) directly onto the daughter card, eliminating the majority of the wire bulk associated with ESC wiring in Qubo. Integrating ESCs onto dedicated cards enhances the modularity and maintainability of the system, reducing the risk of wiring failures and simplifying the overall electrical layout. The new power card design improves upon the current power and control board by incorporating better circuit protection and isolated DC/DC converters with integrated heat sinks. The team is currently testing their assumptions about the eFuses using a development board, with promising results. This power card provides controlled circuit protection against transient events, ensuring a more reliable power distribution system and mitigating the risk of damage from power shorts. By isolating power components and improving heat management, the team aims to enhance the overall durability and performance of Qubo's electrical system.

D. Embedded System

Entering this school year, the firmware of the robot was controlled by several ICs and ROS nodes running on the main Jetson computer. While this came with the benefits of unifying the computer hardware and codebase, this also came with some downsides that emerged at competition in 2023. In particular, the thruster controller IC (a PCA9685) was poorly soldered and came apart during shipping. The unified computer hardware made it difficult to debug and diagnose whether there was a software or hardware fault, an issue which could be resolved by finer control at the hardware level, that is, implementing microcontrollers on the robot.

The solution was to replace both the PCA9685 PWM generator and the BlueRobotics ESCs with STM32 B-G431B-ESC1 boards [2]. These have the benefit of placing an STM32 G4-series microcontroller at each ESC, each having the ability to communicate over a CAN bus or receive control instructions over PWM as with the old BlueRobotics ESCs. Furthermore, these ESCs would offer the ability to have finer control over how the thrusters accelerate, perhaps to optimize current consumption. Using a communication protocol like CAN also enables the team to add more embedded devices to the robot with little additional effort beyond writing firmware for the embedded device itself, such as power monitoring, diagnostics displayed to an OLED screen, etc.

Though significant progress was made on this solution, it was not implemented on the robot due to how close the expected implementation date was with the shipping deadline. The team instead opted to continue to use the same code for thruster control, this time running on the new electrical system in the robot. This way minimal additional testing would be necessary for the software, enabling the team to focus their testing efforts on the hardware instead. It is expected that this system will be implemented on daughter cards next year.

E. Localization and Control Systems

Previously, the team used only a subset of the sensor information available from the system; velocity, angular, and vertical position was directly measured, and the vision systems on the robot provided relative horizontal positioning and guidance. The goal for this year was to take advantage of all available sensors, to improve accuracy and functionality of Qubo's localization. A filter is used to combine similar measurements from different devices to get an accurate state, which enables positional and velocity tracking on all six axes of motion.

These localization improvements provided a more refined control system as well. Using estimates of previously untracked states, the controls team was able to implement cascade PID feedback controllers on all six axes of motion, with the innermost layer controlling Qubo's velocities, and the outermost layer contolling Qubo's positions. With each run, the team was able to better refine the accuracy and stability of Qubo's movements.

For high-level autonomy and planning the team opted to use behavior trees to replace a very rudimentary state machine from last year. Behavior trees allow for more reactivity to different potential states and conditions encountered each run, facilitate increase modularity in code, simplify the process of translating changes in the team's strategy for autonomy, and in general simplify specifications for Qubo's more complex behaviors.

F. 2bo

Resulting from the team's onboarding process this year, one of the team's new members proposed a follower robot project, named 2bo. 2bo was originally designed to fulfill two purposes: inter-vehicle communication and the marker dropper task. Due to timeline concerns, the team is aiming to achieve inter-vehicle communication by attaching a hydrophone on 2bo, and a pinger on Qubo. A very simple custom communications protocol is implemented on the sonar in which Qubo gives 2bo very rough heading information so as to prevent the two robots from colliding. With enough time, 2bo will also be equipped with a camera and a marker dropper to complete the marker dropper task. This comes with the added benefit of navigation ease near the marker dropper bin, since 2bo is significantly smaller than Qubo.

Fig. 5: Rendered CAD model of 2bo.

III. Testing Strategy

In an effort to increase the reliability of Qubo during competition, this year R@M has put testing at the forefront of its development process. Time for testing was incorporated into every project timeline, along with leeway to anticipate iterations. This was an effective change from last year as creating new, unique designs from scratch creates variability and leaves room for error. The team's failure to account for these steps last year led to design changes and end effector integration the week before competition. All new systems, from the pneumatic system to each end effector and the backplane, were systematically tested on a strict timeline and in parallel. This included waterproof testing for the torpedo launcher and multiple enclosures, rapid prototyping throughout the design process, and productive pool tests that iterated methodically on progress, limiting blowback if something went wrong. Overall, Qubo's increase in reliability is credited to a focus on systematic testing from start to finish.

A. Mechanical System Testing

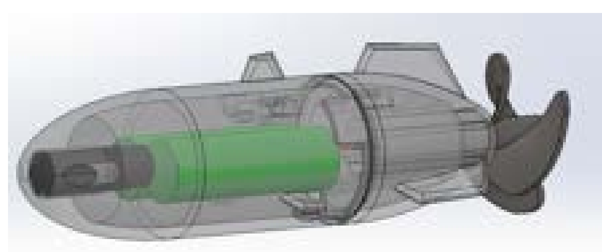

Fig. 6: Rendered CAD model of the newly developed torpedoes emphasizing their internal electronics.

To inform the design of the powered torpedo, the following were tested as the project progressed: motor activation, balance, buoyancy, water resistance at depth, travel distance, and ability to eject from the barrel. Early tests for the project largely focused on improving the circuit, through which redundant components were removed and the circuit was optimized for simplicity. The initial design called for a normally closed reed switch which subsequent tests proved to be unreliable as it would become easily magnetized, getting stuck closed. This led to the motor switching being handled by a micro limit switch which was extremely reliable and made handheld testing much easier. Additionally as physical torpedoes started to be manufactured waterproofing was not focused on much and was only observed by breaking open torpedoes to check for water. Since there had not been tests at depths greater than two feet not much water entered the hull.

On the other hand, releasing the torpedo in the lab sink proved that the motor and supercapacitor configuration was not sufficient, when it could not travel far or fast. This was solved by wiring the supercapacitors in series, doubling the voltage whilst accepting the decrease in runtime (wiring capacitors in series halves the capacitance which dictates the runtime in this case), and by buying larger, more powerful, motors. As the project progressed the supercapacitors were upgraded too from 2.7V, 3.3F to 3.0V, 10F which allowed a much greater runtime. In this vein further handheld testing was able to refine the shape of the torpedo to be more efficient in water.

While solving this, however, balance and waterproofing continued to be extremely difficult as balance testing required repeatedly floating the torpedo in the water, looking at which side floated, opening it back up, hot gluing in some weight on the side that floated, and then closing it back up to start again. While it would've been ideal to solve this problem in the CAD, the circuitry at the time was produced without a board, just floating in the hull which added a great deal of random chance to the process. Waterproofing testing likely led to the most changes as it exposed a lot of flaws with the design at the time, namely: hot glue for sealing, PLA torpedoes, wires being used as electrodes, and the limit switch with a membrane. To test the ability for the torpedo to stay watertight, the torpedo was weighed, plunged down to 7ft (the depth of the Irving pool, a worst case for the torpedo) for 2-10 min on a long conduit pole, and then weighed again to measure the water weight gain. The waterproofness was also measured qualitatively by listening to the amount of water inside. Once this test was accounted for, the hot glue was swapped for quick setting epoxy, PLA was swapped for clear, SLA printed resin, wire electrodes were swapped for 2mm diameter metal prongs, and the limit switch was exchanged for an omnipolar hall-effect switch which allowed the torpedo hull to be sealed much more effectively.

At this point tests waterproofing was no longer a big issue, and previous tests for shooting the torpedo inside the barrels were largely positive. These tests left a very reliable, durable, and consistent torpedo that was able to meet its original design requirements well.

B. Low-Level System Testing

The goal of low-level testing was to ensure the system had motor control functionality and was able to receive data from the sensors. This was done incrementally while integrating the system to make debugging as efficient as possible.

The software team developed a suite of testing utilities for checking functionality of various peripherals on the robot. Thrusters are run at various speeds outside of water to check that they function, and that they have the correct orientation. This is because when the robot is opened and the thrusters are worked on, the PWM circuit may have reversed polarity, which negates the orientation of positive spin on the thrusters. Since the same PCA9685 PWM generator IC is used for controlling PWM for the pneumatics solenoids, the software was extended to test solenoid functionality.

The DVL on Qubo was integrated and tested by taking advantage of the web server that is running on the DVL computer. Simply visiting the website when connected to the robot's network confirms that the DVL is on and responding to motion. When working on it outside of water it is submerged in a dish of water to prevent it from overheating, as the datasheet recommends.

Testing for the new electrical backplane developed this year was also straightforward. Since no new features were added to the electrical system (when compared to last year), testing simply consists of confirming that Qubo's behavior is the same as last year, which is done by running the same tests that are used for last year's system.

C. High-Level System Testing

The first round of testing was to verify that Qubo performs competition tasks in the same way as last year, even with the new hardware and end effectors installed on the robot. This was done by running the exact same pre-qualification code as last year, to provide a basis for updating controls software.

With that basis established, the next step was to write new controls code to utilize the new end effectors installed on Qubo, which has not yet been done at the time of writing this report.

Acknowledgments

Robotics @ Maryland would like to thank the Space Systems Laboratory at the NBRF for lending their lab, time, and tools to the team. The team would also like to thank Dr. Akin specifically for acting as the team advisor over the years, as well as the new advisors Dr. Mitchell and Dr. Zhang. The team was grateful to Ivan Penskiy for allowing the team to use space and tools in the new Robotics and Autonomy lab in the new IDEA Factory. R@M also thanks the Aerospace, Electrical and Computer Engineering, Mechanical Engineering and Computer Science departments for lending their space, time, and money to the team. Additionally, the team thanks Robotic Research LLC, the Mechanical Engineering Department and the Maryland Robotics Center for their generous donations.

References

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[2] STM32 ESCs. https://www.st.com/en/evaluation-tools/b-g431b-esc1.html

[3] Robot Operating System, Foxy Fitzroy. https://docs.ros.org/en/foxy/index.html
[4] WaterLinked, DVL-A50. https://waterlinked.github.io/dvl/dvl-a50/

Appendix A: Members

Mechanical

Dillon Capalongo
Dominik Blahó
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Daniel Gregory
William Trasatti
Sahil Mehta
Ryan Buchler
Khoa Nguyen
Giselle Doh
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Sam Bentz
Nicolas Zefeng Lei Cai
Joshua Ehizibolo
Tommy Wolcott

Electrical

Erik Chapman
Brian Zagalsky
Kurt Kovacs
Daniel McLawhorn
David Nahorniac

Software

Alexander Yelovich
Jeffrey Fisher
Ishaan Ghosh
Thomas Li
Adam Malyshev
Jai Rastogi
Leo Jiang
Max Jin
Eric Xu
Brant Jiang
Grace Cai
Sai Jayanthi
Amin Boukari
Neha Rajasekaran
Alvin Shen
Jai Patel
Aditya Shelke

Twobo

Michael LeVesque
Harshita Kalbhor

Business

Rebecca Recant
Nikolai Weichbrod
Anushka Kaluskar

Appendix B: Outreach

One of R@M's primary goals this year was community involvement. Last summer, the team developed an onboarding program to help ease new members into the world of robotics; the program lasted through the Fall semester. Newcomers were placed into groups and assigned team leads that would guide them through building their own catamaran (which is much simpler than waterproofing a submarine). In addition to fostering a welcoming environment and encouraging others to breakthrough into robotics, R@M built a presence within the wider University of Maryland community, working closely with several departments:

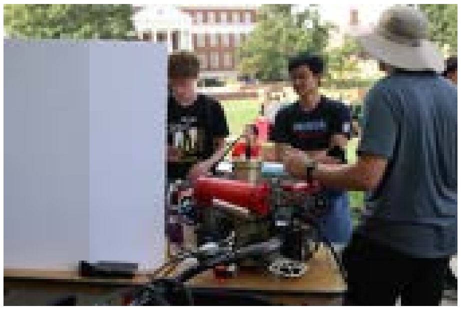
- A. James Clark School of Engineering
- Department of Aerospace
- Department of Electrical and Computer Engineering
- Department of Mechanical Engineering
- Smith School of Business
- Department of Computer Science
- Maryland Robotics Center
- Space Systems Laboratory

Throughout the year, R@M remained at the forefront of university robotics by assisting with outreach, presentations, and networking events with these departments in return for their support.
Some examples of such events are listed:

- Leading tours of R@M's labs for high school and prospective UMD students as well as industry professionals through the Maryland Robotics Center
- Hosting a Design Review each semester for members and UMD students to attend
- Providing feedback for summer camp programs with CoderPie
- Attending various University of Maryland fairs letting young children play with R@M's robots
- Taking interviews with the on-campus newspaper
- Co-hosting events with other engineering organizations, including Women in Engineering events

R@M also added an additional project this past year, increasing the number of projects to three. In addition to Qubo, the team hosts Testudog, a robotic dog aiming to compete in IEEE's Quadruped challenge, as well as Terraformers, a Mars rover team designed to compete in the University Rover Challenge. The team also officially added a business branch in partnership with the university's Smith School of Business under Snider Consulting group for help with organizing outreach events.

R@M leading a tour of the IDEA Factory



Presenting Qubo to new students at the First Look Fair

R@M leadership at the Lockheed Martin Symposium presenting their projects

R@M members at the Spring 2024 Qubo Design Review

Appendix C: Component List

Component	Vendor	Model/Type	Specs	Custom / Purchased	Cost	Year of Purchase
Buoyancy Control	NBRF Stock	Foam	Purple	Custom	$0	N/A
Frame	Custom	N/A	Aluminum, Water Jetted	Custom	$200	2017
Waterproof Housing	Blue Robotics	6in	Acrylic and Aluminum Endcaps	Purchased	$400	2022
Waterproof Connectors	Blue Robotics	Penetrators	M10 Potted Connectors	Purchased	$5	2022
Thrusters	Blue Robotics	T200	11.2 lbf forward thrust, 350 watt	Purchased	$200	2017
Motor Control	Blue Robotics	Basic ESC	7-26 V, 30 amps max	Purchased	$36 x 8	2017
PWM control	NXP Semiconductors	PCA9685	16 PWM channels	Purchased	$14.95 x 2	2023
Air Tank	Maddog	N/A	Aluminum, 20 oz.	Purchased	$28.95	2023
Solenoids	WIC Valve	3V210	0.25 in. 3 Way, 2 Position	Purchased	$26.52 x 4	2023
Pistons	SMC	NCMB075-0100S	0.75 in. Bore, 1 in. Stroke, 0.25 in. Rod	Purchased	$26.71 x 4	2023
Check Valves	BONOMI	100012LF-1/4”	Brass 0.25 in. 400 psi	Purchased	$24.24 x 2	2023
Battery	Gens Ace	GA-B-45C-5000-4S1P-Deans	14.8v, 5000mah	Purchased	$36	2017
Converter	Custom PCB		12V, 5V, Fuse, Current and Voltage Monitoring	Custom	$50	2017
Main Computer	Nvidia	Jetson Xavier NX	16 GB RAM	Purchased	$699	2023
Internal Comm Network	Ethernet, USB, I^2C, CAN Bus					
External Comm Network	Ethernet, Sonar					
AHRS	Vectornav	VN-100	2° accuracy heading and tilt	Purchased	$1,100	2023
DVL	WaterLinked	DVL-A50	±3.75 m/s range, ±0.4% accuracy	Purchased	$6,950	2024
Vision	Stereolabs	ZED 2i	HD Stereo Camera	Purchased	$500	2023
Vision	Allied Vision	Mako G-131C	1280 x 1024 GigE Camera	Purchased	$450	2017

Algorithms: Vision	OpenCV	Various basic vision processing algorithms	N/A	N/A
Algorithms: Other	Kalman Filter	State estimation and sensor fusion	N/A	N/A
Programming Language 1	C++14	N/A		
Programming Language 2	Python 3	N/A		
Programming Language 3	C11/Armv6-M/Armv7E-M	N/A		
Open-Source Software	ROS2 Foxy Fitzroy	N/A		
Open-Source Software	Docker	N/A		