Columbia University in the city of New York

Columbia University

TECHNICAL REPORT

2024 MATE ROV Competition

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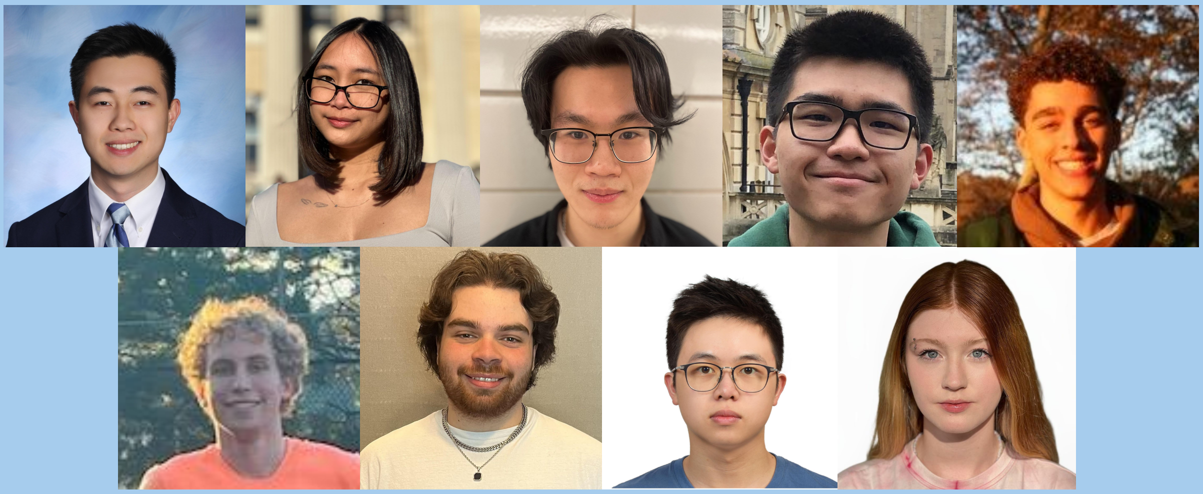
ABSTRACT

The Columbia University Robotics Club (CURC) is an interdisciplinary student engineering organization that manages three projects every year. Among those projects is the Underwater Remotely Operated Vehicle (ROV) project in which students design and engineer an ROV to navigate bodies of water, monitor marine life, and service underwater infrastructure.

ROAR-E 2 is a revision of ROAR-E 1, CURC's first fully engineered ROV. Incorporated within a modular and streamlined frame, the ROV is equipped with six T200 thrusters, three cameras, and a 90-degree-pivoting end effector. In addition to the ROV, the team has engineered a vertical profiling float inspired by the NSF's GO-BGC Float initiative.

The development of ROAR-E 2 is the culmination of seven months of intensive research, planning, and development by CURC's 9-person team. This technical document provides an insight into the engineering processes, principles, and challenges faced by CURC members throughout the creation of ROAR-E 2.



PROJECT MANAGEMENT

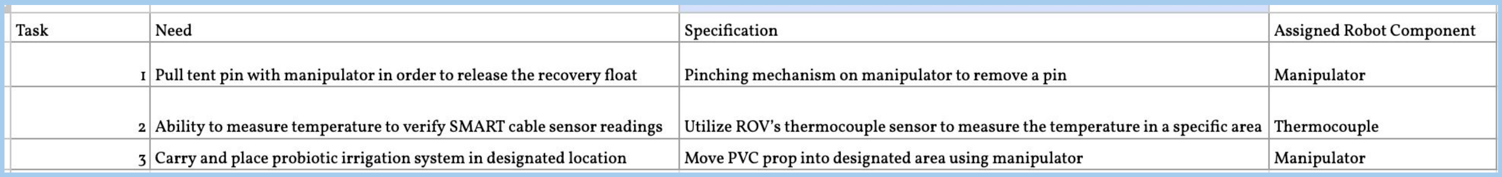
Design Process

The following design process guided the design of components in ROAR-E 1 [1].

1. Problem Definition
2. Background Research
3. Requirement Specification
4. Concept Development
5. Concept Selection
6. Detail Design
7. Manufacturing, Testing, and Revision

For each component, the design process begins with a clear, and precise definition of the problem to be addressed. Then, background research is conducted on existing works. For product demonstration tasks, a needs and specification table was used to develop a clear list of design requirements. Concept development occurs over several group meetings, after which several concepts are generated. Pugh tables are used for concept selection. After concept selection, detail design begins and the design is iterated several times to improve manufacturability, safety, and reliability, while minimizing cost and weight. Commercial-off-the-shelf (COTS) parts are used in the design either when a part that could be manufactured in-house would fail to meet CURC's safety, reliability, and manufacturability standards, or when cost and weight are prohibitive.

Manufacturing and testing begins after the detail design is sufficiently developed, and design revisions are made as necessary.



Task	Need	Specification	Assigned Robot Component
1	Pull tent pin with manipulator in order to release the recovery float	Pinching mechanism on manipulator to remove a pin	Manipulator
2	Ability to measure temperature to verify SMART cable sensor readings	Utilize ROV's thermocouple sensor to measure the temperature in a specific area	Thermocouple
3	Carry and place probiotic irrigation system in designated location	Move PVC prop into designated area using manipulator	Manipulator

Fig. 1: Needs and Specifications chart

DESIGN RATIONALE

FRAME

The frame serves as a rigid mounting system for all of the components of the ROV. It houses the thrusters, electronics system, cameras, buoyancy, and manipulator.

We made our frame out of 15x15mm 6063 aluminum extrusions and 6061 aluminum brackets. We sourced the aluminum extrusions from an online vendor, and completed all machining tasks utilizing our university's machine shop. The extrusions are sturdy and rigid but they are still relatively lightweight since they are aluminum. We considered using plastic sheet stock as the foundation for our frame, but upon closer examination, we determined that plastic sheet-based design requires large cross-sections for rigidity, which increase drag and reduce the maneuverability of the ROV. An additional benefit of using aluminum extrusions is that all components and hardware can be mounted using hex bolts and t-slot mounting gear. This allows for incredible ease when it comes to adopting alternate component configurations.

To join the aluminum extrusions together, we utilized 18-8 fasteners, coupled with 6061 profile brackets, sourced from commercially available vendors. Based on prior experience with tear-out failure of bolts in extrusion t-slot channels during unexpected collisions, redundancy was incorporated into the design. With 5 fasteners per bracket, and 2 brackets per connection between extrusions, forces in typical use are reliably distributed across bolts, thereby minimizing
risk of tear-out failure during typical use.

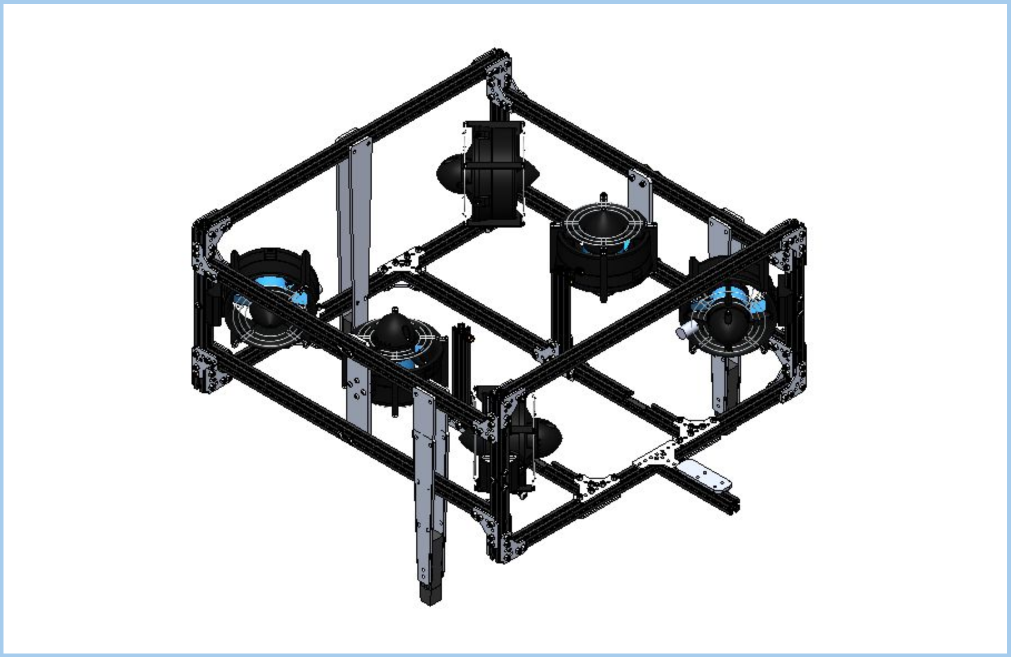


Fig. 2: ROARE 1 Frame

PROPULSION

Our current configuration consists of 6 Blue Robotics T200 waterproof thrusters, arranged in the following configuration: Two in the front of the ROV oriented in the vertical axis, complemented by two in the back of the ROV, also oriented in the vertical axis. These four thrusters can be fired in pairs of two or altogether to provide pitch control. In the center of the ROV, we mounted two more thrusters in a horizontal position to allow for horizontal translation of the robot. These horizontal thrusters can also be fired independently, in order to provide the ROV with the ability to control its yaw positioning.

This configuration is a deviation from the original vectored configuration of ROARE 1. The vectored drive was initially desirable for its the precision it could provide along the yaw axis. However, after extensive testing of this configuration, the team deemed precision along the vertical axis was most important for stability and to compensate for the buoyancy imbalance of the ROV due to the air-filled electronics enclosure skewed off the center of mass. This made it near impossible for the ROV to reliably surface and descend, leading us to reconsider our options in terms of propulsion configurations. Additionally, the team decided that the primarily motivation for the vectored configuration—the ability to strafe—would minimally be utilized during the competition, so we decided to forgo this configuration in favor of a more traditional design.


Fig. 3: Blue Robotics T200 Thruster

Upon testing the traditional thruster configuration, we found that the ROV was much more maneuverable and responded as expected with regard to the inputs that we directed it with. This proved to be an enormous advancement, as we were able to now focus on the tasks of the competition, knowing that the ROV would be able to predictably traverse the waters of the competition pool.

BUOYANCY

Devices for buoyancy affect the stability of the ROV and the behavior of the ROV when unpowered. A commercially available 1 L water bottles was chosen to provide additional buoyancy, as the ROV was negatively buoyant without it.

With additional buoyancy and no ballast, the ROV is positively buoyant. To precisely determine the amount of ballast that is needed to achieve neutral buoyancy, which is desirable for enhanced maneuverability, the water bottles are temporarily filled with water until the ROV becomes neutrally buoyant, the mass of the water inside the bottles is determined, and a ballast of corresponding mass is placed inside the center, bottom of the enclosure.

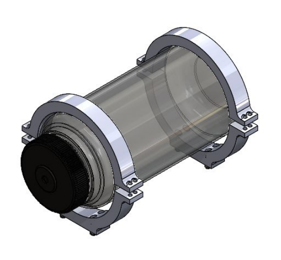


Fig. 4: Variable ballast water bottle

TETHER

A 100ft tether facilitates communication between the ROV and the surface control station. The tether consists of three cat6 cables and one 2-core power cable. The power cable provides the 48 volts from the power supply to the ROV. Two of the cat6 cables send PWM signals from the surface to the thrusters, servos, and lights as well as sends up the data collected by the onboard temperature sensor. The remaining cat6 cable transfers the 3 USB camera feeds to the surface. Strain relief protects electronics on both ends of the tether from damage when the tether is pulled (see Safety). After two cat6 cables failed and had to be replaced, more attention was put into relieving strain not only on the electronics but on the cables themselves. A load-bearing wire was added and clamped together with the cables—tugging on the tether results in the wire being tugged and not the critical power- and signal-providing cables.

Fig. 4: 3D-printed load-bearing wire clamp

ELECTRONICS

The onboard electronics consist of 2 48V-12V converter, a 12V-5V converter; 7 ESCs for the thrusters and manipulator motor; and the USB-over-Ethernet transmitter. The electronics are housed in a watertight Polycase enclosure.

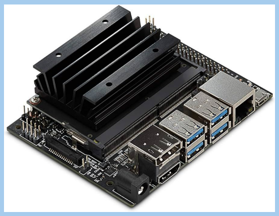


Fig. 5: Jetson Nano

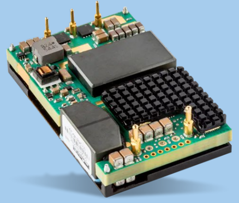


Fig. 6: 48V-12V Converter

CONTROL STATION

Fig. 7: Control Station

The control station is contained in a custom-machined polycase enclosure. It consist of a monitor for viewing camera feeds and dashboards; a Jetson Nano for processing; a servo driver for controlling the PWM motors and servos; an Xbox controller for piloting; and the receiver for the USB-over-Ethernet camera feeds.

MANIPULATOR

ROARE 2's end effector consists of a Blue Robotics M200 motor driving a lead screw, which then drives a lead screw nut along guide rails, thus achieving the opening and closing of the gripping elements by changing the geometry of the linkages. The four jaw serrated mechanism provides enough grip for the various PVC sizes the ROV will be interacting with. Additionally, to two of the claw tips, screws were added to allow pinching of small objects, such as the removal of the tent pin in Task 3.1. The entire manipulator is attached to a servo that can pivot between a horizontal and vertical position; the ability to grab objects from above minimizes the risk of pushing objects further away due to the presence of the pool floor on the other side.

The lead screw is threaded only partially while the rest of the shaft has a smaller OD than the lead screw nut's ID. This was done to prevent applying too much force to and breaking the claw if the motor pushes the nut beyond the necessary length of the lead screw. Should the nut get to that point, the motor could run continuously without damaging the entire claw. However, this requires the ROV to return to the surface for a manual reset.

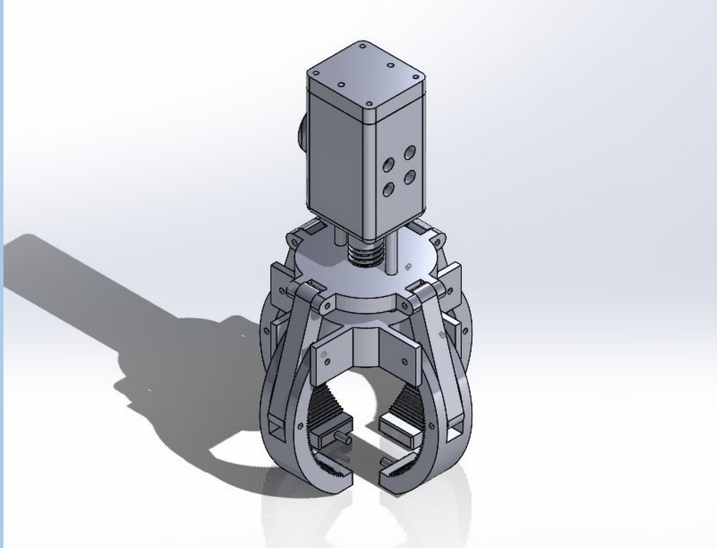


Fig. 8: Manipulator

CAMERA

Navigation is facilitated by three onboard cameras: two endoscope cameras and one Intel depth camera. Endoscope cameras were used for their small profile and inexpensiveness—they can be waterproofed by potting with epoxy with no concern for damaging its electronics. The depth camera provides the main view and is housed within the electronics enclosure.

FLOAT

In addition to the ROV, the team engineered a vertical-profiling float equipped with a buoyancy engine, a depth sensor, and wireless transmission capabilities.

The buoyancy control system is a 100 ml Luer Lock plastic syringe controlled by an L16-S Actuonix Miniature linear actuator and powered by an Arduino Nano. Initially, the float will be positively buoyant and, when released, will float on the pool's surface. Then the linear actuator will activate and exert a force on the syringe to intake water from the pool. Once the linear actuator achieves its fully retracted position, the float will begin to sink. The depth sensor will be logging its data every five seconds and will inform the Arduino when the float has reached the bottom of the pool.

Our float utilizes a cylindrical hull design. This geometry is defined by the 50mm diameter Cast Acrylic Plastic Watertight Enclosure Tube by Blue Robotics which encloses all of the essential elements of the device. An acrylic plastic material minimizes the volume of the hull since acrylic is lighter compared to various metals. Minimizing the volume of the hull helps reduce the effect of external moments from the deep sea environment and supports a system where the buoyancy engine directs the greatest differences of mass. The O-ring lead-in and the precision machined O-ring interface were influential specifications of this product that led us to favor it for our project since maintaining the dehydrated interior for electronics components was critical to its role.

For data collection, we opted to use the Blue Robotics Bar02 Ultra High Resolution Depth/Pressure Sensor with depth capabilities up to 10m. The water depth resolution of this device is highly accurate at 0.16mm, and its compatibility with the Arduino Nano were key motivators in our selection process. The Arduino Nano, which directs both the linear actuator and the pressure/depth sensor, was selected because of its compact size and its cost-efficiency.

The float is deployed by the ROV which holds the float horizontally. When the ROV releases the float, the float naturally uprights itself. An internal tilt switch then triggers the vertical profiling program.

Fig. 9: Float

SYSTEMS INTERCONNECTED DIAGRAM

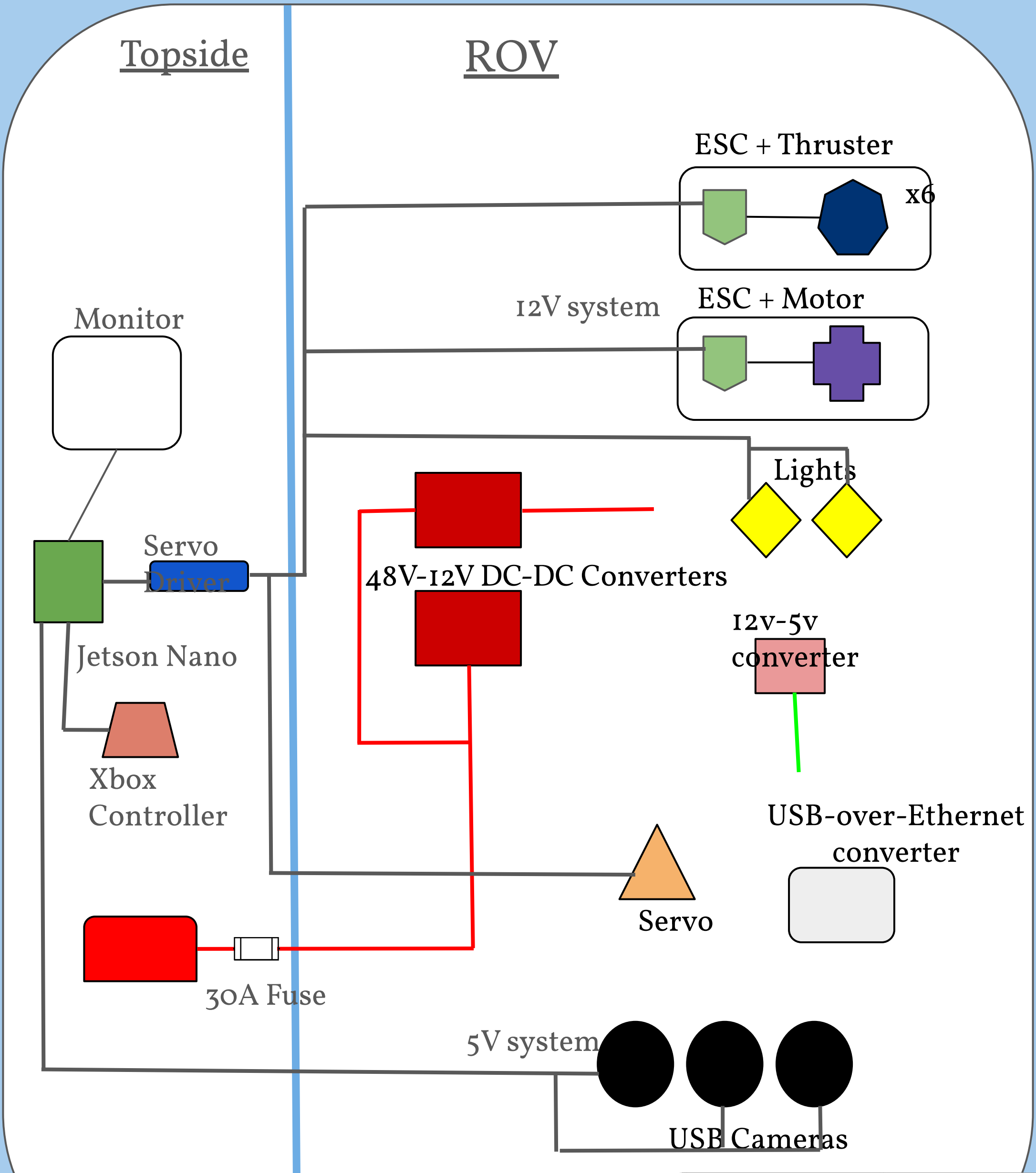
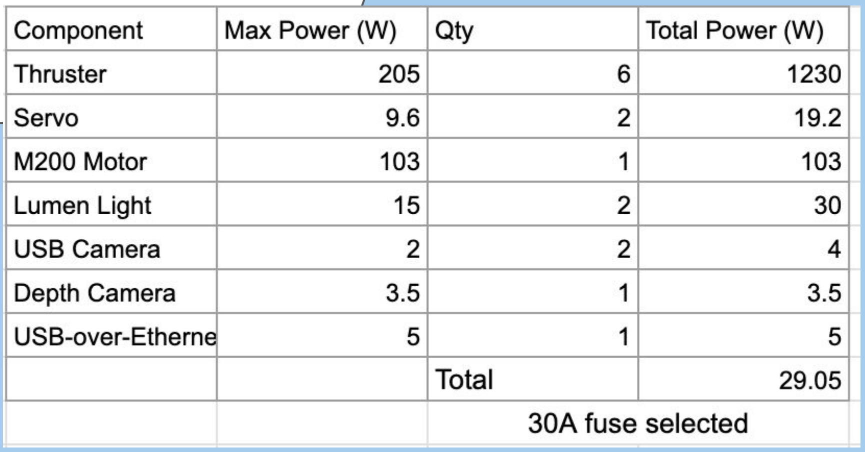


Fig. 10 : Systems Interconnected Diagram

Fig. 11: Fuse Calculations



Component	Max Power (W)	Qty	Total Power (W)
Thruster	205	6	1230
Servo	9.6	2	19.2
M200 Motor	103	1	103
Lumen Light	15	2	30
USB Camera	2	2	4
Depth Camera	3.5	1	3.5
USB-over-Etherne	5	1	5
		Total	29.05
		30A fuse selected	

SAFETY

Operational

CURC is committed to following safety procedures and guidelines in the workshop, while operating machinery and the ROV, and in the design of the ROVs mechanics and electronics. In-house machining is conducted in the Mechanical Teaching Laboratory, which is always supervised by lab staff and when machinery is in use.

In CURC, machining is done by team members who have taken a machining course or have received training from lab staff. CURC members must take an official safety training course before using any machines in the laboratory. CURC members do not train other members on machines for safety and liability reasons. Machining is never done alone, safety glasses are always worn in the machining area, loose hair and clothing are secured, close toed shoes are worn, and machining is done with lab-recommended feeds and speeds.

Additive manufacturing requests are submitted to lab staff who are responsible for safely using and maintaining 3D printers.Safety glasses are worn when soldering or handling electronics, and capacitors are discharged before handling.

Features

In order to minimize the threat of injury that can be inflicted by the ROV itself, we did our best to try and eliminate all dangerous components on the ROV.

Another aspect that we deemed to be dangerous is the various hex nuts that protruded from our frame. These were essentially just exposed screws that posed a risk of damaging their surroundings by the exposed sharp threads on the screw. In order to mitigate this, we simply purchased an abundance of cap nuts, which remove this risk altogether while also improving the aesthetics of the robot itself.

Another aspect was the thruster guards, which prevent insertion of objects larger than the gratings on the guards into the region of the thruster where the propeller is. The thruster guards that we had unfortunately did not fit the newer model of thruster that we purchased so we turned once again to additive manufacturing methods in order to create a custom solution. With these installed, we are confident in that our ROV poses minimal risk to individuals around it.

Fig. 12: Thruster Guard

Fig 13: Cap nuts

TESTING & TROUBLESHOOTING

Our team withstood a plethora of unexpected issues and complications during the long route of creating the ROV. In order to address them, our team learned to utilize various testing techniques that minimize the amount of time lost. When something did not work, we adopted an incremental approach to determine the source of the error. Say, for example that a servo was not turning when directed by the game controller. Instead of wondering why this was the case and trying to determine the solution from a high-level perspective, we would analyze each component of the servo and determine from there where the issue originated.

In practice, we would start at the servo driver board, and determine if the board was getting power. If so, then we would measure the output to see if PWM was being produced. If this was true, we checked to see if the signal was being pushed through the wire to the servo itself, etc etc. This incremental approach may seem like overkill for such a single servo motor, but when circuits began to become very complex, breaking it down into its fundamental components was critical for the team to understand where an error might have originated.

CHALLENGES

Non-technical

Retention of team members has been a challenge due to their status as students, juggling classes and various extracurricular commitments. The demanding midterm and finals seasons severely limited the time available for project work, and by the beginning of May, members were moving off campus to return home or start their internships. This resulted in a handful of team members cramming to finish the ROV during the last few weeks before the deadline.

The most critical challenge jeopardizing CURC's qualification for the world championships was securing a suitable site to record the qualifying video. Despite submitting a request in advance to utilize Columbia University Dodge Fitness Center pool, the team encountered unanticipated delays in receiving approval to test ROAR-E 2. Once approval was granted, the team was quoted $600/hr to use the pool.

As we did not find this to be a feasible solution, we were forced to search elsewhere. Other facilities in New York were either unsuitable or unwilling to accommodate our needs, due to factors such as safety and permit requirements. Finally, we were able to get in contact with member at the Columbia Lamont-Doherty Earth Observatory campus, where, after an hour each way journey, we were finally able to test our robot.

Technical

A major technical issue that delayed our progress for the better part of three days was related to the tether. Our ROV was receiving inputs correctly during the day of testing, but on the next day, upon powering up the ROV, the motors would simply stutter and jitter without rhyme or reason. After rewiring the entire control box in search of a disconnected cable clamp or similar, we were left without a solution as to what might be causing the problem.

At the junction of further testing and logical deduction, we were finally able to determine that our tether was the source of the issue. By testing our thrusters with shorter cables and verifying that they worked correctly, we concluded that the tether had become damaged and was distorting and or attenuating the PWM signals being sent through it. In order to remedy this, we purchased new ethernet cables, and designed a superior cable stress reduction system in order to prevent the same problem from occurring in the future.

Another issue that we faced was due to the buoyancy of the ROV. Upon activating the vertically-mounted thrusters to surface the ROV, we noticed that the ROV would arc upon its path to the surface. We determined that this was due to the buoyancy of the ROV not being on the center of mass, which would tilt one end of the ROV and cause for it to adopt the curved trajectory. Upon changing our buoyancy system and thruster configuration, we were able to resolve this issue.

FUTURE IMPROVEMENTS

From a software perspective, in the future we would be interested in utilizing gyroscope accelerometer and altimeters to help refine and stabilize the ROV's movement during the course of its usage. Additionally, we may consider using ROS if it is determined that having a more compartmentalized software architecture is beneficial. Electrically, we would like to design custom PCBs to increase the reliability and reduce the profile of the electronics used throughout ROAR-E 2. As a team, we will also reflect on ways to increase member retention, attract new attract new talent, and increase knowledge transfer.

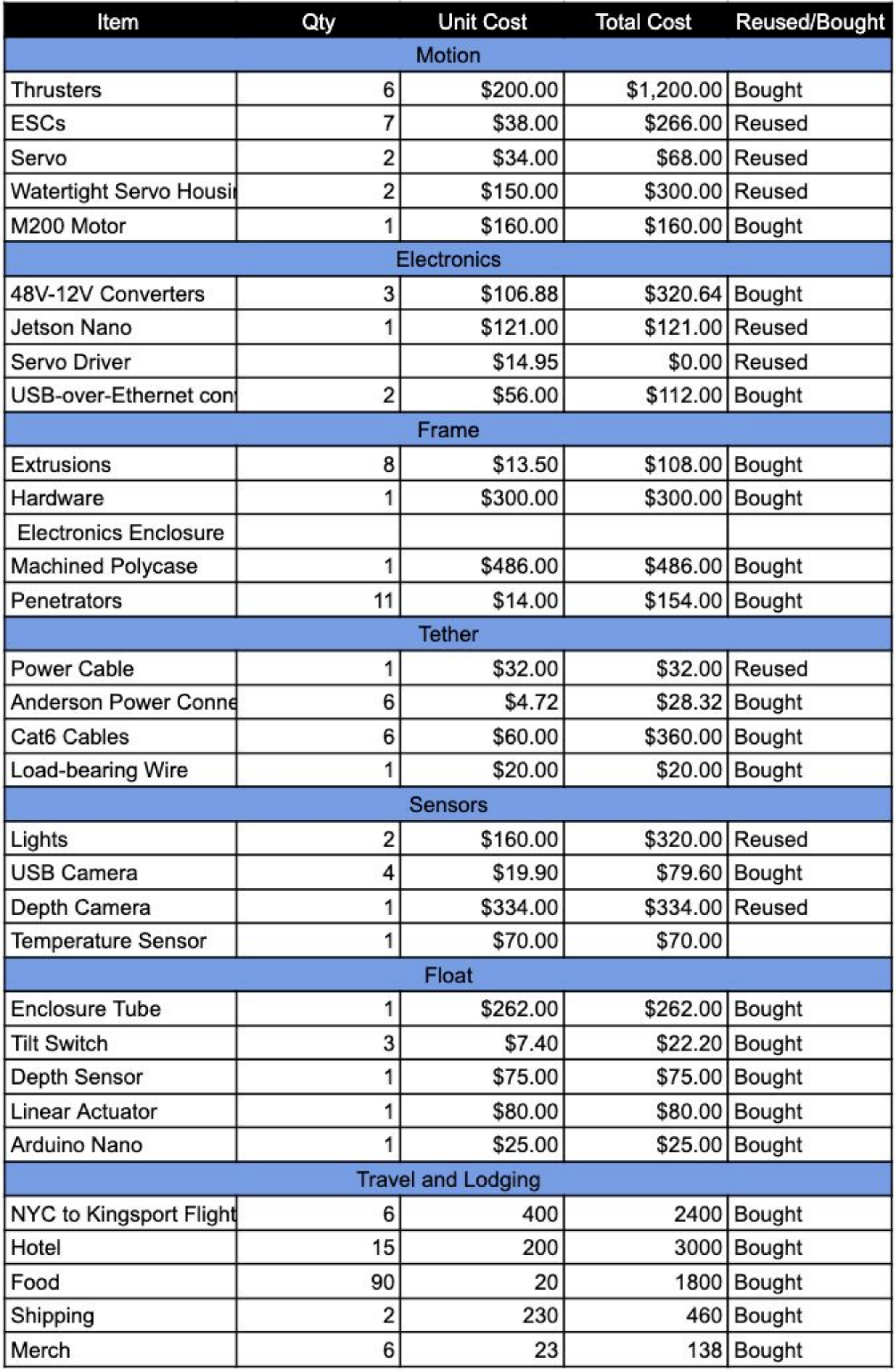
ACKNOWLEDGEMENTS

CURC would like to acknowledge the following people for their support and contributions to the ROV project:

Amoy Ansell-Poirier - COMPETITION CHAPERONE
Daniela Duron Garcia- ASSISTANT MANAGER OF INSTRUCTIONAL LABORATORIES
Amanda Lombardo - MANAGER OF INSTRUCTIONAL LABORATORIES
Jorge Casas - MACHINIST TECHNICIAN
Hod Lipson - CURC ADVISOR; CO-DIRECTOR, MAKERSPACE FACILITY
Nick Frearson - LAMONT OBSERVATORY OF COLUMBIA UNIVERSITY
Ryan Harris - LAMONT OBSERVATORY OF COLUMBIA UNIVERSITY
Shih-Fu Chang - DEAN OF THE FU FOUNDATION SCHOOL OF ENGINEERING AND APPLIED SCIENCE

AND THE CU ROBOTICS CLUB EXECUTIVE BOARD AND GENERAL BODY

ACCOUNTING



Item	Qty	Unit Cost	Total Cost	Reused/Bought
Motion				
Thrusters	6	$200.00	$1,200.00	Bought
ESCs	7	$38.00	$266.00	Reused
Servo	2	$34.00	$68.00	Reused
Watertight Servo Housi	2	$150.00	$300.00	Reused
M200 Motor	1	$160.00	$160.00	Bought
Electronics				
48V-12V Converters	3	$106.88	$320.64	Bought
Jetson Nano	1	$121.00	$121.00	Reused
Servo Driver		$14.95	$0.00	Reused
USB-over-Ethernet con	2	$56.00	$112.00	Bought
Frame				
Extrusions	8	$13.50	$108.00	Bought
Hardware	1	$300.00	$300.00	Bought
Electronics Enclosure				
Machined Polycase	1	$486.00	$486.00	Bought
Penetrators	11	$14.00	$154.00	Bought
Tether				
Power Cable	1	$32.00	$32.00	Reused
Anderson Power Conne	6	$4.72	$28.32	Bought
Cat6 Cables	6	$60.00	$360.00	Bought
Load-bearing Wire	1	$20.00	$20.00	Bought
Sensors				
Lights	2	$160.00	$320.00	Reused
USB Camera	4	$19.90	$79.60	Bought
Depth Camera	1	$334.00	$334.00	Reused
Temperature Sensor	1	$70.00	$70.00	
Float				
Enclosure Tube	1	$262.00	$262.00	Bought
Tilt Switch	3	$7.40	$22.20	Bought
Depth Sensor	1	$75.00	$75.00	Bought
Linear Actuator	1	$80.00	$80.00	Bought
Arduino Nano	1	$25.00	$25.00	Bought
Travel and Lodging				
NYC to Kingsport Flight	6	400	2400	Bought
Hotel	15	200	3000	Bought
Food	90	20	1800	Bought
Shipping	2	230	460	Bought
Merch	6	23	138	Bought

Fig 14: Accounting