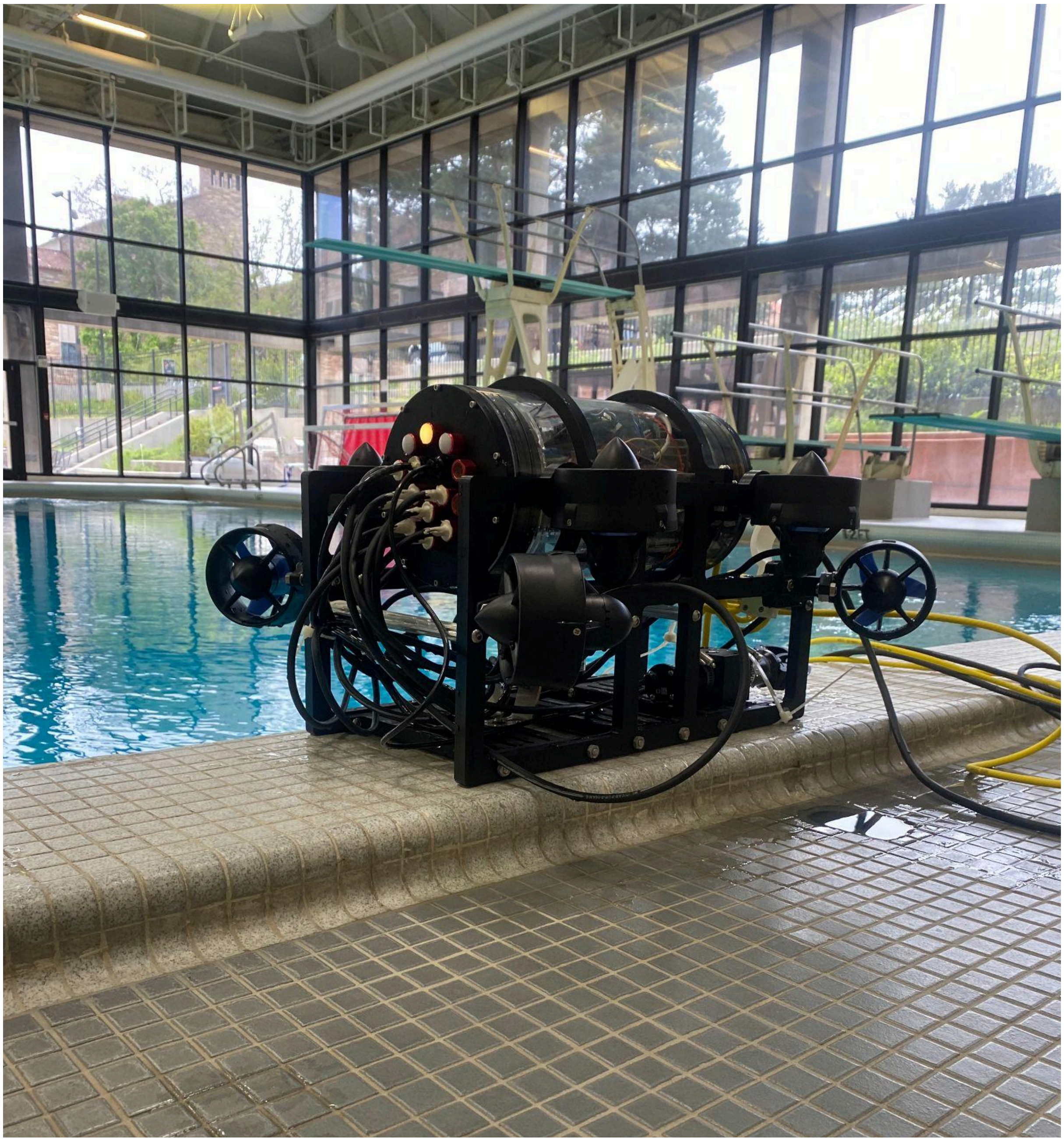
Colorado Robosub
MATE 2024
Technical Documentation



Teamwork 3
Company Description 3
Leadership Personnel 4
Project Management 4
Design Rationale 5
Engineering Rationale 5
Innovation 7
Problem Solving 9
Systems Approach 9
Structure 10
Systems 11
Electrical and Controls 11
Propulsion 12
Buoyancy 14
Payload & Tools 14
Build vs Buy, New vs Used 17
Systems Integration Diagram 18
Safety 18
Safety Overview 18
Safety Checklists: 19
Critical Analysis 20
Testing and Troubleshooting 20
Accounting 22
Budget 22
Funding Sources 22
Cost accounting 22

Acknowledgements and References:

Colorado Robosub would like to formally thank the University of Colorado at Boulder, SOAC (Student Organization Allocations Committee), UCEC (The University of Colorado Engineering Council), and EEF (Engineering Excellence Fund) for their administrative and financial contributions. Due to their contributions, Colorado Robosub has the necessary support to provide STEM-inclined students with interdisciplinary engineering experience developing underwater vehicles.

Teamwork

Company Description

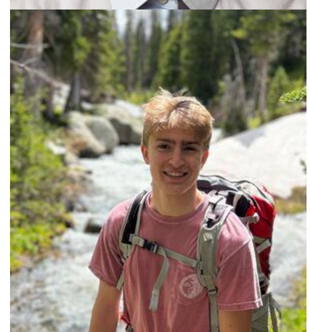
The University of Colorado Boulder's Colorado Robosub team has competed in the MATE ROV competition for the past 4 years, making its first appearance in the World Championships during the 2022-23 season. In the past the team has used our now outgoing ROV, Lazarus, to win the Rocky Mountain regional once and placing 10th in the pool at last year's world championships. This experience with world championships inspired the company to make a new ROV, Chimera, to make use of the lessons learned from Lazurus and create a "MATE ROV Beast".

Chimera accomplishes this task in several different ways, the first of which is by reducing weight. Lazarus had a heavy aluminum block on its back side, adding unnecessary weight that Chimera does not have. Chimera has also been constructed to move more freely, and provide a stronger platform for control software. Chimera does this by having two sets of motors, one of which is responsible for motion in the x, y and yaw directions, and the other which is responsible for motion in the z, pitch, and roll directions. This results in much smoother and more controlled movements, as well as the ability to easily move diagonally, in any direction of the pilot's choice.

Chimera's ability to easily navigate any environment and manipulate a wide range of objects makes it a very promising vehicle for conservation activities, such as removing waste, identifying diseased coral, and gathering data from various sources. The company plans to test this capability in real life by diving in a local reservoir and extracting trash and other debris from areas that humans can not reach.

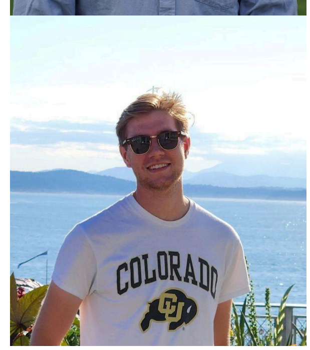
Leadership Personnel

President: Xavier O'Keefe
Oversaw systems level development of the sub, recruiting, finances, and software development. Ensured that all members of the team were heard and had the resources to complete their projects. Responsible for creating deadlines, plans to meet these deadlines, and ensuring that the team stayed focused.



Electrical Lead: Liam Harris
Completed the initial Chimera frame design during Summer 2023. During the school year oversaw all Chimera electrical design and integration.

Mechanical Lead: Ben Partee
Oversaw all mechanical and systems integration projects. Managed sub-team responsibilities and divided tasks amongst mechanical team members. Projects include the design and fabrication of all mechanical components: frame and structural members, gripper rotation mechanism, electronics rack, sensor mounts, and propulsion system



Software Lead: Jake Tucker
Designed and built part of the system software stack for interaction with the hardware. Managed and distributed development tasks to other members of the software team, much of them related to the camera systems and MateROV task development.

Project Management

In order to maximize the effectiveness of our work during the relatively short MATE ROV design cycle, it was of critical importance the team be well-organized. Experienced members of the team placed emphasis on providing learning opportunities for younger members on the team in order to align our development efforts with our team's mission statement.

Colorado RoboSub distributed resources into three development subteams: electrical, mechanical, and software. Each subteam had a specific goal in mind and utilized processes, knowledge, and practices specific to that subteam to meet its goal. The electrical team was responsible for creating a safe and reliable power system for Chimera. The mechanical team focused on designing and manufacturing our new frame and motor mounts, as well as designing new mechanisms to solve problems as they arose. The software team created an all-new software stack with a focus around bringing in new technology and designing for future autonomy.

Once the Colorado RoboSub company began developing a solution to the MATE ROV competition mission objectives, the team developed a comprehensive development schedule. This development schedule included dates for design reviews, code commits, and testing. Major milestones were to: complete all elements of the physical design by October 1st, finalize design by November 1st, finalize our software and electrical systems by February 1st, finish construction by March 1st, and finish our MATE video by May 1st. Objectives in the new year were not hit due to our funding distribution being delayed by 3 months, so all items scheduled to be completed in 2024 were completed relatively simultaneously in late April.

In order to complete the MATE ROV competition mission objectives, our company met twice a week at the University of Colorado Boulder's Engineering Center. Testing was done at the University of Colorado at Boulder Recreation Center diving well with a maximum depth of 14 feet. Colorado RoboSub has been able to complete mission objectives and solve day to day problems by establishing an organized development lifecycle, consolidating administrative and technical resources across sub-teams, and engaging in frequent in-person development and testing meetings. One staple of this process has been our weekly updates, which provide the entire team with information about projects around the club, as well as provide opportunities for all members of the team to provide feedback on designs and concepts.

Design Rationale

Engineering Rationale

For the first time in three years, Colorado Robosub is bringing an entirely new ROV platform to competition: Chimera. Chimera was designed last summer following the MATE 2023 World Championship. At the competition's closing ceremonies, Phil Beierl (Oceaneering VP of Aerospace and Defense Technologies) presented the Oceaneering Isurus, shown below. He called it "the fastest work-class AUV in the world." In MATE, the name of the game is working fast, so naturally Chimera took heavy inspiration from the Isurus.

Figure 1: Oceaneering's "Isurus" ROV

This biggest inspiration Chimera took from Isurus is its motor configuration. Four angularly vectored motors allow the sub to move in all 360 degrees easily. Chimera also utilizes high-mounted vertical thrusters. In the real world, this helps keep thrusters clear from debris. For our applications, it keeps space open lower on the frame for cameras or tools. Where the motor configuration differs from Isurus is in the fact that Chimera has four vertical thrusters instead of two. This is because our previous subs have struggled with pitch stability due to buoyancy issues and when lifting heavy objects. Therefore we chose to add another two vertical thrusters to increase the pitch control capability.

Once a motor configuration was decided, the frame design began. Our previous design utilized a 6" enclosure. It worked well, so that size was chosen again for Chimera. The two remaining features that needed to be taken into account for the frame design were a large bay for tools and cameras and a structural point that could support the lifting of heavy loads. Once all these factors were considered, the team arrived at the frame design shown below.

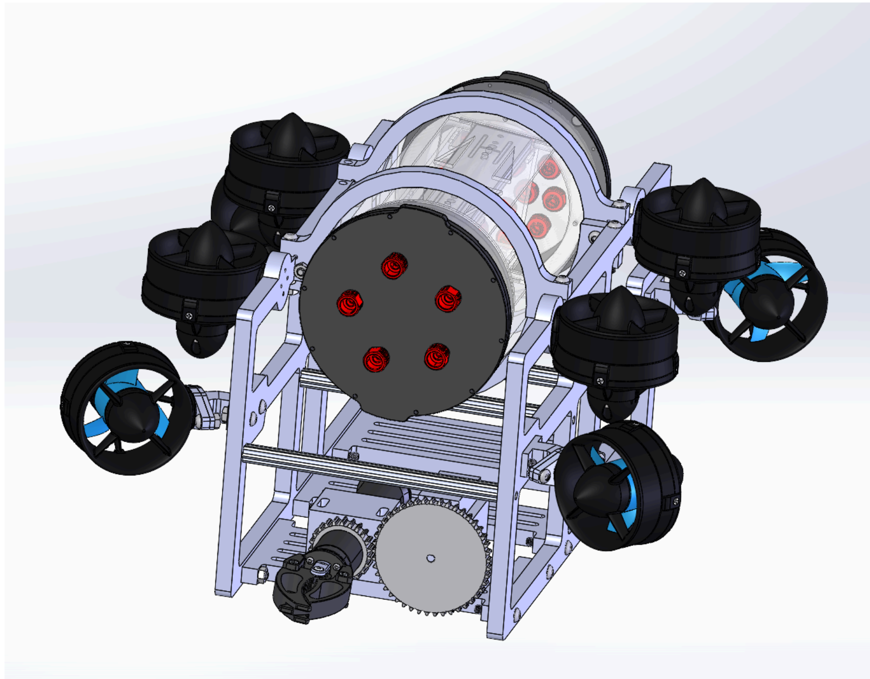


Figure 2: Full Assembly View of Chimera

Innovation

Apart from an entirely new frame design, Colorado Robosub is bringing several other upgrades to competition this year. Arguably the most impressive of these is the sliding electronics rack. The electronics rack on our old sub, Lazarus, can only be described as awful. It was heavy, too large, and was secured very poorly. All this made it extremely cumbersome to open to work on the electronics. When designing Chimera, we decided to make the electronics rack a major focus. Using off the shelf drawer slides, acrylic, and intelligent penetrator placement we created a completely novel design that opens and closes with ease.

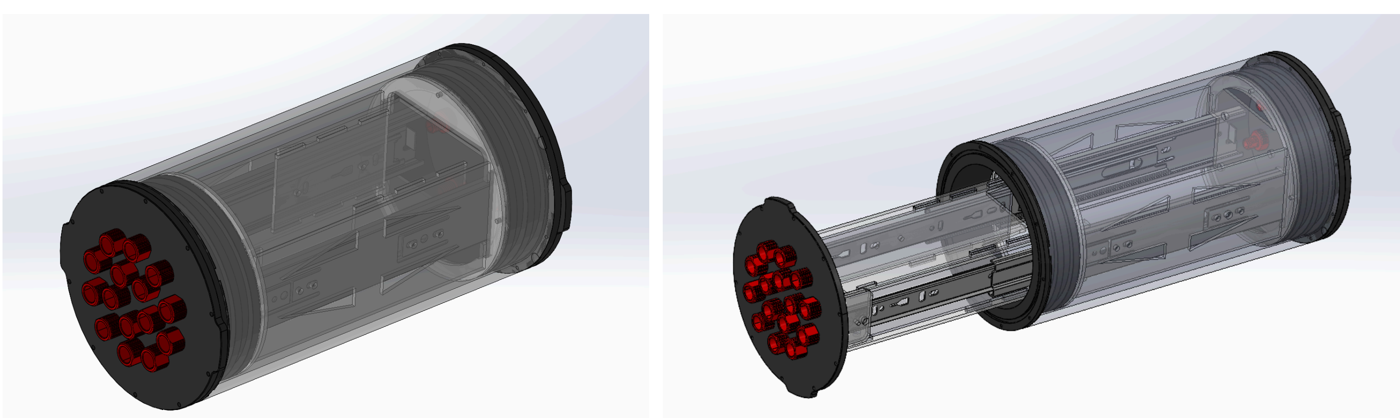


Figure 3: Electronics Rack With Sliding Capability Shown

One of the other innovations Colorado Robosub has developed this year is more of a creative solution to a problem we created. If we were to run all eight Blue Robotics T200 thrusters onboard at their maximum continuous operating current of 17 amps simultaneously, it would require over 130 amps of current. This would melt most wires, crash the computer, and potentially blow a fuse. Luckily, there is virtually no scenario where all eight motors would need to operate at full throttle simultaneously. Using variable control modes, we can control which set of thrusters (lateral/vertical) receive more current at any time in software. This ultimately allows us to switch between prioritizing current to the vertical or lateral thrusters depending on what the sub is doing at that time. If Chimera needs to surface or dive, the vertical thrusters are prioritized. If Chimera is already at the right operating depth and needs to move around, lateral current is prioritized.

The final innovation we'll discuss is our gripper rotation gearing. Over the past couple years, Colorado Robosub has been continuously improving on a mechanism to rotate a Blue Robotics gripper. This allows us to adjust our main tool for different game pieces on the fly. Last year we thought we'd arrived at a final design: two sprockets, one driven by a servo, linked by a timing belt. However, the ball valve introduced this year has forced us to adapt once again. The previous design limited gripper rotation to less than 360 degrees. This means we would have to take multiple attempts to turn the ball valve, slowing us down. To address this, we changed the gear ratio of the sprockets to roughly 2:1. Now we can rotate nearly 600 degrees to fully open the ball valve with only 300 degrees of servo rotation.

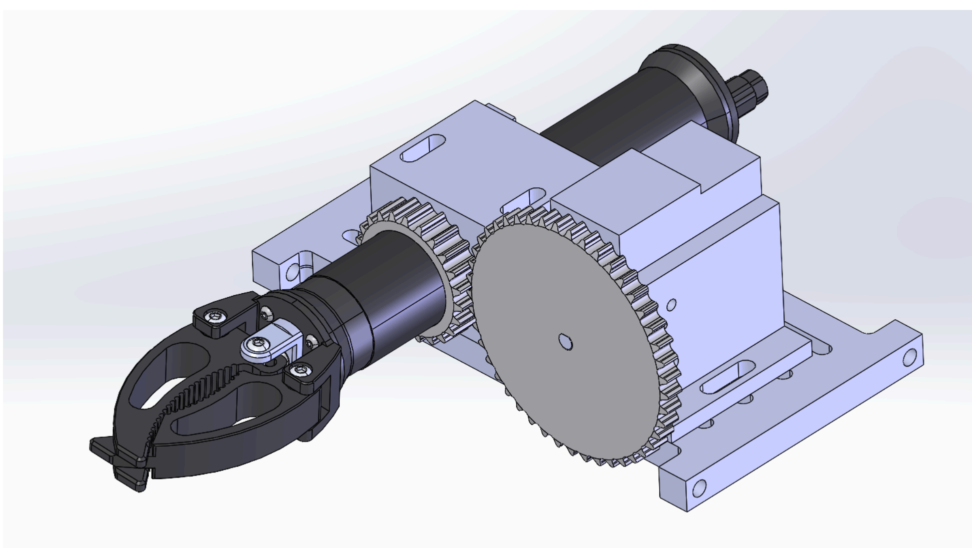


Figure 4: Gripper Rotation Assembly

Problem Solving

Designing an all-new sub came with many challenges for all subteams. One of the largest design decisions made was to redesign our entire software stack. Our software stack was old and outdated, and we decided to implement several new technologies and frameworks to keep our sub ahead of the competition. After some initial research and development, it became clear that the software we wanted to use would not work natively on our Nvidia Jetson Nano, with the only alternative being a Docker container. This caused us to pause and evaluate a) if we should go ahead with the new technology, and b) how to go about implementing it. After researching performance tradeoffs between these two options we found that the Docker container would be equally as performant as a native build, so we decided to continue on with the implementation of the new technology. This in turn created several other roadblocks, which were each dealt with by thoroughly laying out the problem, collaborating with the entire software team, researching on the internet, and finally coming to a consensus with the whole team.

Another problem we solved was the placement of our sub's motors. In order to determine placements and orientations of the motors we performed a trade study, evaluating two designs against several criteria, including controllability, dollar cost, electrical power cost, and maneuverability. The team leadership was tasked with providing preliminary designs and arguments for each orientation, and the rest of the team was asked to evaluate each design and provide their input during our weekly team meetings. Leads were allowed to be creative with their designs, with many drawing inspiration from industrial grade ROVs and some even drawing inspiration from nature. This forum-based approach to design decisions allowed us to evaluate each design in depth, move elements of designs around, and eventually come to a solution that represented a sum of the entire team's ideas.

Systems Approach

One of the largest contributors to our success was the amount of experience we had on the team. This really showed when approaching the entire system design and integration. Every aspect of every system on the team was scrutinized by experienced eyes to ensure optimal performance and functionality. The electrical system was designed to provide peak performance for our motors, informing our software about the physical limitations of our systems. Our internal wiring was configured to split each of our 4-motor sets in half, with the idea that this would allow for more power distribution at maximum control inputs. Our frame and motor placements were evaluated for controllability, with our roll and pitch motors placed closer to our center of gravity to reduce moments and improve our sub's inherent stability. Our software was created with our physical layout in mind, incorporating different scaling factors for different motors in different drive modes and directions. Gripper and camera placements were evaluated for their impact on our center of mass, and our hull was shifted to place our center of gravity at the middle of the frame. Our IMU was placed as close to the center of gravity as possible to increase accuracy of our sensing, therefore improving the accuracy of our control system.

Implementing a new feature could be frustrating at times, as someone was always making a comment about one system's impact on another. This environment ultimately led to a more holistic design and subsequently a much better product. As a result of this holistic systems-level approach, Chimera shows great promise as an entire system, with very few obvious oversights.

Structure

Although Chimera is built on an entirely new frame (shown below), it pulls many elements from our previous ROV, Lazarus. Like Lazarus', Chimera's frame is made from ½" marine-grade high density polyethylene (HDPE). Beyond our team's previous experience with HDPE, it is relatively cheap, easy to machine, and more than strong enough for our applications. Normally when working with sheet material, the normal (thin) axis is the weakest and most susceptible to deformation. ½" thickness provides plenty of material strength, but the edges of the frame still experienced significant deformation. Because of this, structural churro tubes were added in a few key locations to increase the rigidity of the frame along the thin axis.

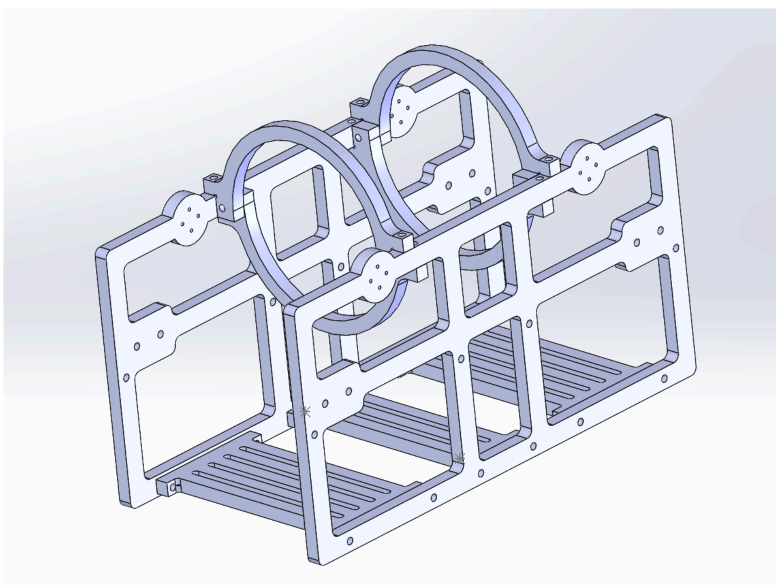


Figure 5: CAD Model of Chimera Frame

One of the "key churro tube locations" mentioned above is directly in the center of the frame, with an opening below it. This was intended to support a hook for lifting heavy and/or loads from below the sub. When loaded from the gripper, Chimera and Lazarus experience large forward pitching moments. This was a huge problem on Lazarus, and heavily informed our decision to add a dedicated heavy-lift point. Lifting from the central hook reduces these moments to virtually zero.

Systems

The overall system design was chosen to provide a platform that would be quicker and more nimble than our last sub, Lazarus, and still allow for us to implement finely-tuned controls for future autonomous tasks. One way we did this was by placing our motors vertically on the corners of our frame to allow for the same 4 motors to control our drive, strafe and yaw axes. Our other 4 motors were placed horizontally with respect to the ground, allowing us to control depth, pitch, and roll axes. We chose BlueRobotics T200 motors because of their ubiquity in the MATE competition, as well as their demonstrated reliability in previous Colorado Robosub projects. These motors were certainly not the cheapest option, but the reliability and proven functionality were more than enough for us to justify these costs. Several other components were purchased from BlueRobotics using the same reasoning. These components were our 6” hull, both end caps, various penetrators, camera casings, Newton Gripper, as well as ESCs.

Chimera’s frame was designed to enable the aforementioned maneuverability and controllability. This was accomplished with in-house design and manufacturing, making use of our talented mechanical team and the facilities at CU Boulder to reduce cost. Motor mounts and thruster guards were also designed in-house and produced via 3D printing, allowing for great prototyping ability as well as low manufacturing cost. The frame was created from High Density PolyEthylene (HDPE), which we found to be nearly neutrally buoyant in water, strong, and easy to work with.

Most of Chimera’s physical design was finished during the summer of 2023, but many more improvements were made upon the release of the 2024 mission tasks. One of the most notable improvements was our gripper rotation mechanism, which is covered in the “Innovation” section. This design required a waterproof servo, which we purchased from BlueTrail robotics. In order to reduce costs we purchased each part separately and then assembled the waterproof casing and servo ourselves. Another parameter of our design that changed to meet mission requirements were our motor mounts - which were redesigned to be more durable and provide a larger lever arm for our motors.

Electrical and Controls

The electrical system (outlined later in the system integration diagram) was designed mainly with overall footprint in mind. Chimera has a smaller hull than Lazarus, so it was essential to reduce the amount of space taken up by the electronics. This had to be done while retaining the same capability. This was done by eliminating some of the unnecessary components that were in Lazarus such as bulky voltage converters, USB hubs, and unnecessary lengths of wires.

In terms of controls, Colorado Robosub has brought a major innovation to competition this year. Last year, we implemented fine and coarse control modes. This year, we implemented lateral and vertical control modes. By switching between these two modes, we can decide which set of motors receives the majority of the 12V current. Our converter limits us to 30 amps total, but each motor can run at up to 17A. The dominant set of motors receives 17 amps, and the other set receives 13 amps.

The electrical system has 2 voltage levels, 5 and 12 volts. The 12 volt level provides power to the majority of the components, including the thrusters, DVL, light, and gripper. The 5 volt supplies power to the Jetson nano, which in turn supplies power to the PWM controller and cameras via USB. The control system uses a mini Maestro PWM controller to interface with the ESCs connected to the thrusters, and the servos in the gripper mechanism. The system uses a combination of user input and a PID controller to maintain the desired position which is determined using data from the DVL. The electrical system is connected to the ground station via the tether, which consists of two cables; a two conductor cable which supplies 48V power and ground to the ROV, and the other is an ethernet cable to provide connection to the onboard computer. Both tether cables are manufactured to be neutrally buoyant to prevent excessive tether pull on the ROV. To further prevent pull a team member is responsible for managing the slack in the cables to prevent tension effects on the ROV. Strain relief was also implemented to reduce tension on the penetrators and potting of the cable.

Propulsion

As mentioned previously, Chimera utilized four angularly configured thrusters in the lateral plane, and four thrusters in the vertical plane. Chimera's main priority when designing our motor configuration was to optimize thrust output in all six degrees of freedom, whilst prioritizing pitch, yaw, forward translation, and vertical translation. The graph below shows theoretical propulsion outputs as a function of the angle in which the thrusters are mounted. From this graph, our team chose an angle of 30 degrees offset from the horizontal plane in order to maximize thrust in our prioritized directions (our team decided to prioritize forward / backward thrust capabilities over sideways thrust due to 2024 competition tasks). Note that the configuration of the vertical thrusters was responsible for pitch and vertical translation, so horizontal thrusters aimed to maximize forward and transverse translations.

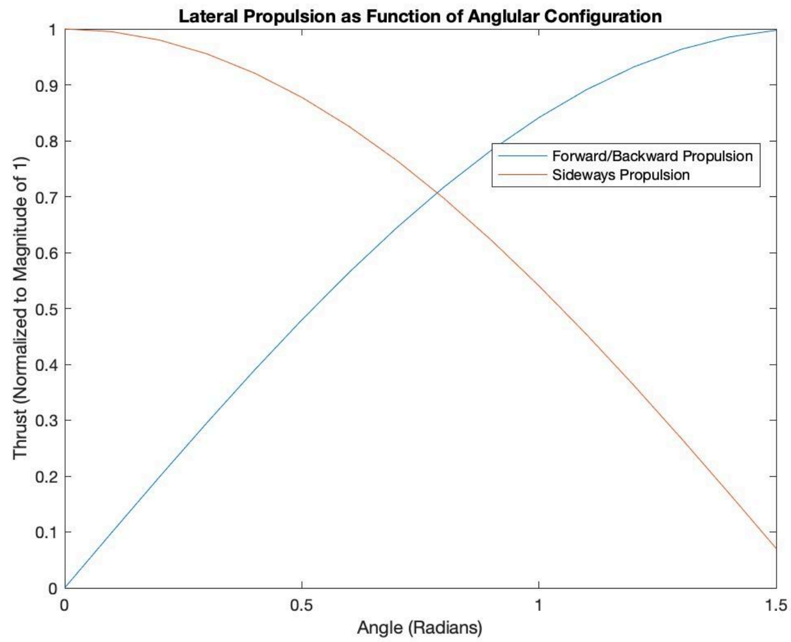


Figure 6: Graph Used To Determine Mounting Angle of Motors

Industry standard Blue Robotics T200 thrusters were chosen due to their high thrust capability and robustness. The thrusters were mounted using a combination of custom designed brackets and mounts. Both the mounts and brackets were fabricated using 3D printed PLA polymer.

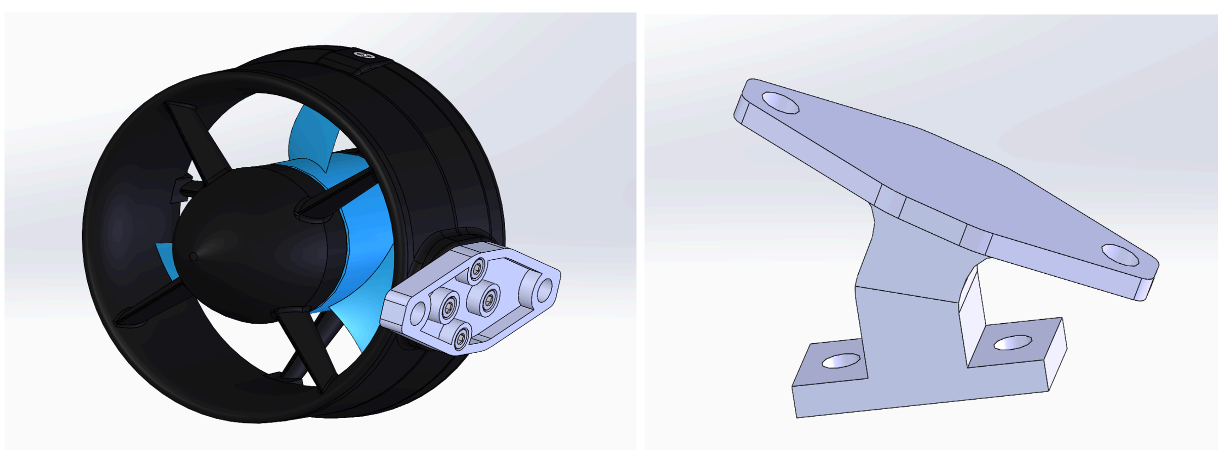


Figure 7: Motor Bracket with T200 Thruster [Left] and Motor Mount [Right]

Buoyancy

Chimera was designed with the intent to to have neutral buoyancy when operating in an aquatic environment. Achieving neutral buoyancy through mechanical design reduced the stress on our software team to implement PID controls to maintain constant position underwater while completing tasks. Our first step to achieve neutral buoyancy was using a positively buoyant material for the entirety of our frame. HDPE not only was ideal for its structural and machinability qualities, but also is also 3% less dense than water. The addition of our lightweight acrylic electronics encasement provided substantial volume, displacing fluid to drastically increase the buoyancy of the overall assembly. Despite these efforts, the addition of sensors, electronics, and other components on the sub added substantial weight, resulting in negative buoyancy upon initial testing. To combat this, our team fastened low density, marine grade foam underneath our electronics rack. The buoyancy force from the foam was sufficient in achieving near neutral buoyancy on Chimera.

Figure 8: Foam Used For Additional Buoyancy

Payload & Tools

Chimera's payload was designed with the intention to optimize performance on the assigned MATE ROV 2024 competition tasks. Chimera's frame was designed with channels along the bottom support members to allow for ease of payload installment. These channels along with holes drilled along the vertical support members of the frame, allowed for complete modularity. This modularity allowed us to easily change the location of components on the sub, as well as leave room for the addition of future components, without the need for a complete redesign of the frame.

The most critical component to the success of Chimera is its Doppler Velocity Log (DVL). The industry standard DVL used on Chimera transmitted instantaneous data of velocity in all three cartesian directions. The DVL transmits a series of sound waves towards the sea bottom and then measures the frequency shift of the reflected echoes. This measured shift allows the DVL to calculate Chimera's speed and direction of travel, when integrated with software controls.

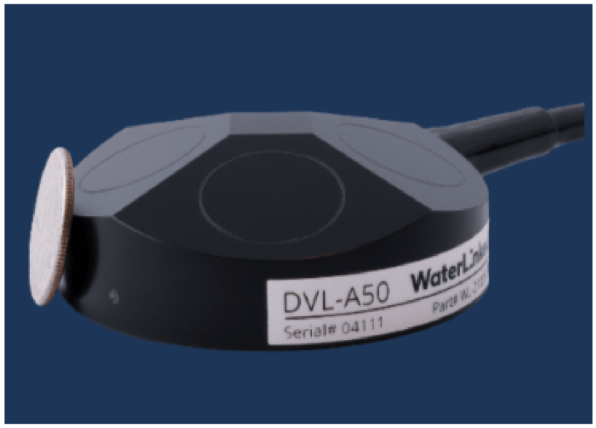


Figure 9: Waterlinked A-50 DVL (Credit Waterlinked)

Another crucial component on Chimera is the gripper and gripper rotation mechanisms. The components within the gripper assembly are as follows: Bluerobotics "Newton Subsea Gripper", high torque waterproof servo motor, custom servo and gripper mounts (3D printed PLA), and custom spur gears (3D printed PLA). As aforementioned, the meshing gear system designed to rotate the gripper allowed for 600 degrees of rotation, which was imperative to completing valve rotation competition tasks. The mounts and gears for the gripper rotation mechanism were designed in CAD software and 3D printed with high strength PLA. Furthermore, the use of hose clamps and a steel shaft key allowed for complete torque transmission from the servo to the gripper gear, whilst doubling as a means of preventing translation of the gripper within its mount. The components listed above were integrated into the frame on the frontal bottom support member channel using 1⁄4" bolt and nut fasteners.

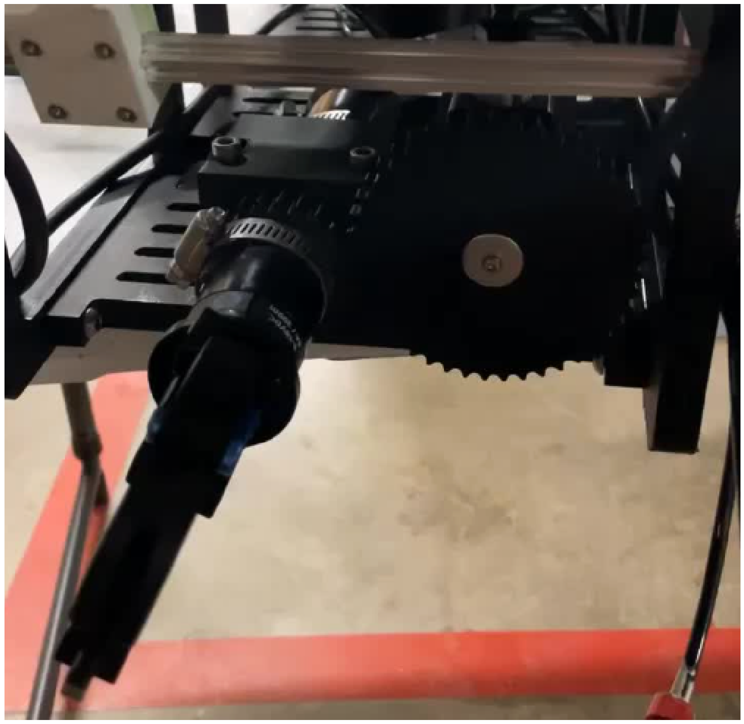


Figure 10: Photograph of rotation mechanism on Chimera

Finally, two cameras were utilized on Chimera in order to give the sub's operator a complete field of view, and vision of the gripper mechanism. This was achieved by mounting one camera aligned parallel with the horizontal plane of the sub, and one at an angle of 45 degrees towards the sea floor. The horizontal camera provided holistic views of the sub when operating its lateral thrusters and traveling long distances. The angled "down-cam" provided a view of the gripper mechanism in order to complete gripper related tasks, and also doubled as a means of viewing the sea floor. We did not find a need for further cameras to complete mission tasks.

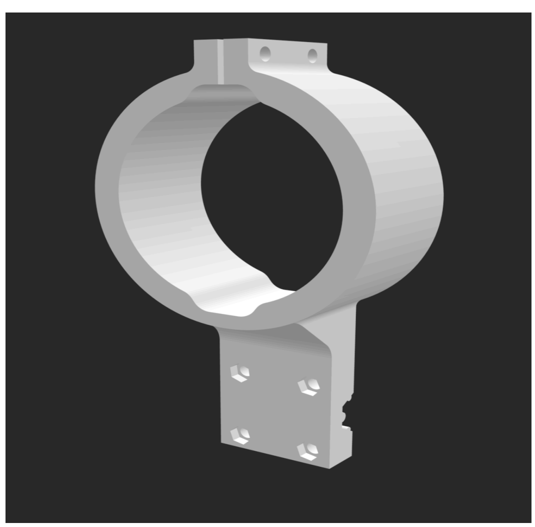


Figure 11: CAD Model of Camera Mount

Build vs Buy, New vs Used

One component we chose to buy over make ourselves was the BlueRobotics Newton Gripper, which costs $640. This gripper has been used by the company in the past, and has proven to be very useful and reliable. During the planning phase of the year, we discussed creating our own gripper from scratch. Assessing the market rate for linear actuators, manufacturing, and waterproofing, we determined that this mission-critical product would cost us a similar amount of money, as well as a significantly larger workload on the team. After assembling the final budget and finding that we could make the gripper purchase work, we decided that it would be best to focus our efforts on the construction of our new ROV, rather than drawing several of our most experienced members away from the core project for several months to develop our own gripper.

Building a new sub required that we buy mostly new components, however some were re-used due to their familiarity to the team and proven functionality. One of these such components was the NVIDIA Jetson Nano, which has provided the team with a reliable computer to run all of our sub's operations from. One benefit of the Jetson is the AI and image processing capability, which we hope to utilize as we move more towards autonomy. We also re-used our Doppler Velocity Logger due to its high degree of accuracy, as well as its astronomical price tag.

Systems Integration Diagram

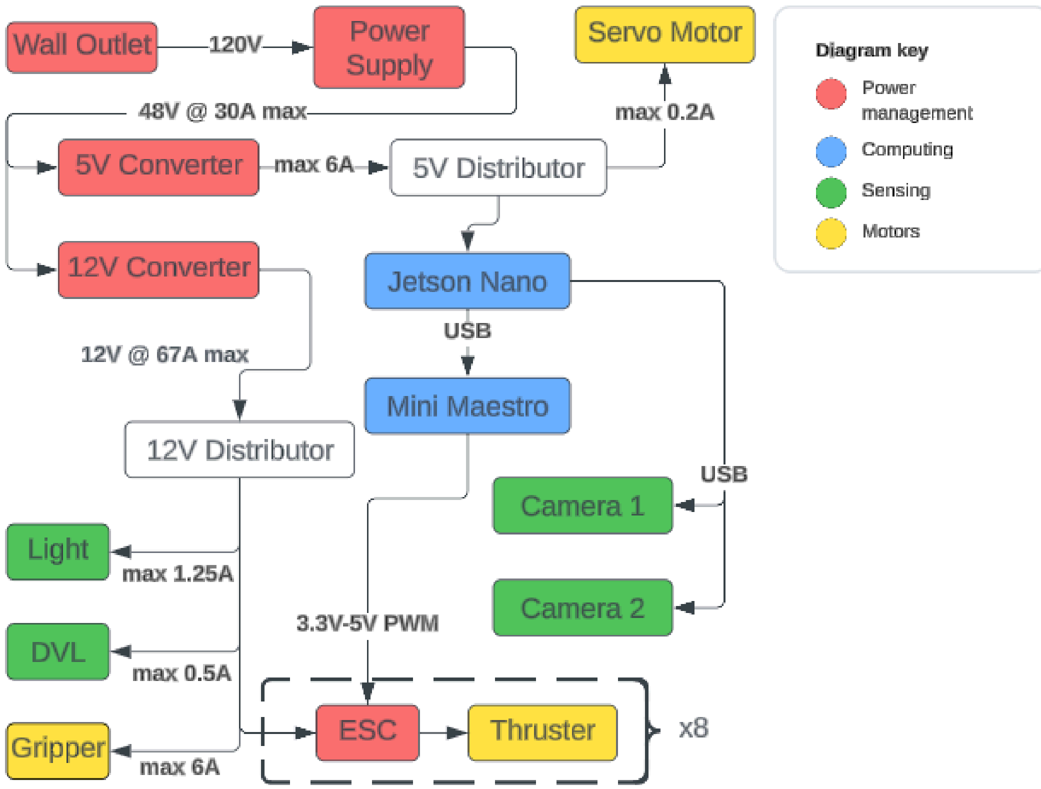


Figure 12: SID for Chimera

Safety

Safety Overview

Safety is of utmost importance at Colorado Robosub. Our mission statement emphasizes our commitment to safety by stating "our program provides a safe, diverse, inclusive, and collaborative environment for students to expand their existing technical skill set and meet other students with similar passions." Having an environment that is safe for our students allows participants to reduce the risk of potential injuries, increase productivity, and be more confident in the work they are pursuing. In addition to our company's history of providing students with technical construction and operation training, our company also implemented many best safety practices.

All new members of Colorado Robosub are provided with onboarding documentation. There is separate onboarding documentation for each sub-team: mechanical, electrical, and software engineering. Each onboarding documentation contains information about how to safely conduct oneself on their respective sub-team. For instance, the mechanical engineering onboarding documentation contains instructions on OSHA (Occupational Safety and Health Administration) PPE (Personal Protective Equipment), the electrical engineering onboarding documentation contains instructions on ESD (Electrostatic Discharge), and the software engineering onboarding documentation contains instructions on code reviews and safely merging production code.

All mechanical engineering employees at the Colorado Robosub company are taught machine shop safety by experienced staff members from the University of Colorado at Boulder. The safety of all employees, students, and nearby individuals is taken into account whenever an action is being performed. All employees are trained before handling potentially dangerous machinery or materials, and new employees receive mentorship from experienced employees to ensure a safe development environment. PPE such as safety glasses, gloves, hearing protection, and closed-toed shoes are required while operating and handling the ROV. In addition to employee safety, our ROV features several safety features including IP-20 thruster guards to protect individuals' fingers from blades of the vessel's six T200 thrusters, redundant watertight seals, and insulated on-board electronics.

Safety Checklists:

Safety Rationale:

Colorado Robosub strives to make all operations as safe as possible. Several members of the team have worked as bike mechanics or manual laborers, and all team members are trained to survey each situation for safety risks. Utmost caution is taken while working with our high voltage components, as well as with university power tools. The company has an informal "rule" that either of these operations can and should not be completed alone, and that every member of the club is responsible for the safety of everyone involved. Giving one's "best effort" is not always enough to ensure safety, so we have developed several safety procedures to ensure that everyone is safe, every time.

Construction Checklist:

- Only approved individuals that have received Colorado Robosub company safety training are allowed to utilize shop equipment and perform work on the ROV.
- Secure shop space and all valuable equipment and materials within the shop space.
- No eating or drinking in the shop space, other than consuming water.
- Utilize necessary PPE depending on the nature of work being performed, and all company employees inside the lab space are required to wear close-toed shoes at all times.
- Be aware of loose clothing, jewelry, and personal body hair when utilizing machinery.
- Clean area, materials, and equipment soon after use.
- Return items to their proper location soon after use.

Operational Checklist:

- ***Pre-Dive***
    - Check the vehicle to ensure that all vent plugs have been sealed.
    - Double check hull seals to verify there has been no damage to o-rings
    - Grease seals with grease once every three to five dives.
    - Bolt hull endcap to bore to prevent possibility of endcap ejection (due to temperature and pressure changes while diving).
- ***During Dive***
    - One team member must always manage the tether while the vehicle is in operation. The tether should be neatly coiled and placed in the immediate vicinity/control of the tether managing individual.
    - The driver must announce to the prop manager before actuating the Newton gripper to prevent incidental pinching or injury.
    - Surface members should watch the vehicle at all times for a sudden burst of air, potentially indicating a leaking enclosure.
    - A software team member must always be ready to kill the vehicle while in the water to prevent the vessel from "running away" or damaging the pool due to inadvertent motion.
    - Before handling the ROV, the vehicles must be disabled (to protect individuals from potential injury caused by thrusters and gripper).

Critical Analysis

Testing and Troubleshooting

Colorado Robosub's vehicle development, testing, and troubleshooting methodology revolved around modular and encapsulated technical advances. Once an encapsulated portion of development was developed, tested, and troubleshooted, then it was incorporated into the larger system. In addition to this, our company completed several system integration tests to determine the effectiveness of multiple modules working together.

Mechanical engineering modules were developed and structurally analyzed in SolidWorks before fabricating and incorporating them into the broader vehicle design. 3D printing was utilized where possible to ensure that mechanisms worked as intended. Electrical engineering modules were isolated and tested with varying power supply inputs and peripherals before integration into the vessel. Electrical and software engineering modules were developed in chunks, with each system being tested separately before being merged together or into the source code.

Once technical modules were functionally verified, the finalized product was fabricated, assembled, and incorporated into the broader vehicle design. Each Colorado Robosub company employee was responsible for a unique module of the technical design and its functionality, testing, and integration success.

After the final product was fabricated, several tests were performed to evaluate the submarine's ability to complete MATE tasks, and make changes where necessary. This testing consisted of driving the sub around to test our control systems and buoyancy. We also tested our gripper, camera, and gripper rotation mechanism in the pool to get a sense of the "battlefield" feel of the controls. One issue that arose during Chimera's testing was buoyancy, which was largely negative. In order to fix this we strategically added foam around the sub to reduce the load on our depth control motors while retaining balance in motion.

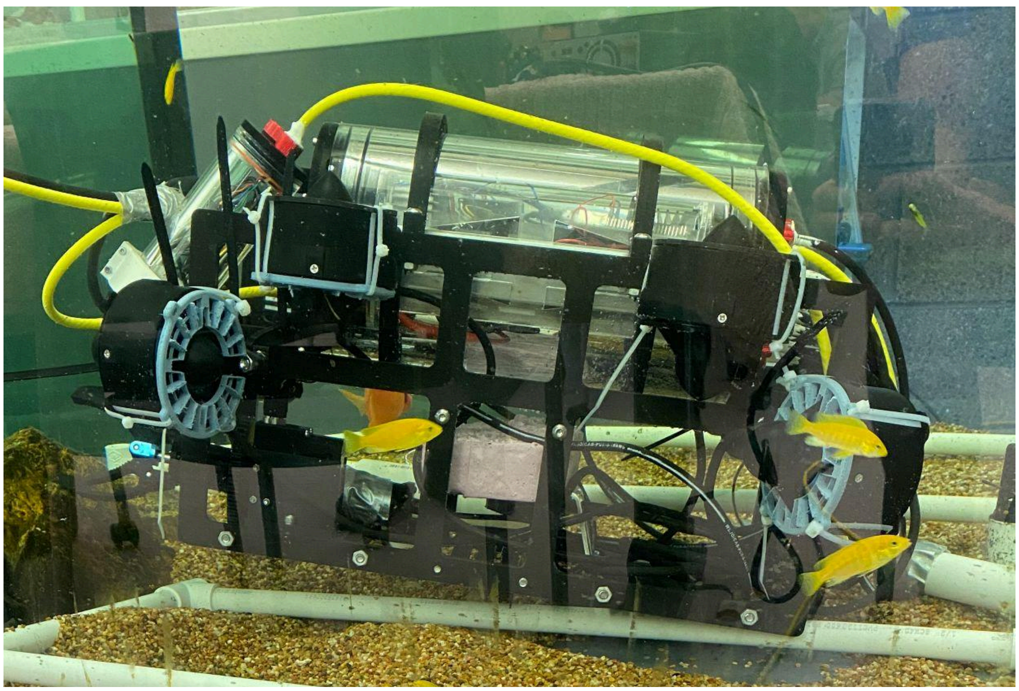


Figure 13: One of Chimera's first dives, where we worked on our buoyancy with some friends

Colorado Robosub's approach to troubleshooting is largely focused around fast fixes, with failures being used as opportunities to improve the next iteration of a design. For example, the first iteration of our gripper rotation mechanism did not secure the gripper tightly enough. This made the mechanism essentially inoperable, but we did not want to wait for another development and production cycle to continue testing. Zip ties and duct tape were used to properly secure the gripper, allowing for testing to continue until a new design could be made. Many problems are solved in similar ways.

Accounting

Budget

2023-2024 Chimera Cost Summary		Item Description	Type	Budget	Project Cost	Variance
Production ROV Expenses						
	Frame and Hull	BlueRobotics 6" enclosure, HDPE sheet	Purchased	$ 723.87	$ 723.87	$ -
	Thrusters	8 BlueRobotics T100 Thrusters + ESCs	Re-Used	$ 1,600.00	$ -	$ 1,600.00
	Mission Components	**Cameras, Camera Housings, Gripper, Servos**	Purchased	$ 1,220.00	$ 1,153.73	$ 66.27
	Electronics and Connectors	Power Converters, Servo Controllers, Cat5, Wires, etc.	Purchased	$ 313.98	$ 356.82	$ (42.84)
	Tether	BlueRobotics Ethernet/power tether	Purchased	$ 735.00	$ 735.00	$ -
	Sensing	Used as a high accuracy, ubiquitous sensor since 2019	Re-Used	$ 7,500.00	$ -	$ 7,500.00
	Misc Materials	Acrylic, bolts, nuts, 3D printing, etc.	Purchased	$ 400.00	$ 423.39	$ (23.39)
Total Chimera Expenses				**$ 12,492.85**	**$ 3,392.81**	**$ 9,100.04**
Non-Chimera expenses						
	Float Materials, Electronics	Acrylic end caps, PVC Pipe, Stepper Motor, Arduino, etc.	Purchased	$ 206.31	$ 227.30	$ (227.30)
Total Non-Chimera Expenses				**$ 206.31**	**$ 227.30**	**$ (227.30)**
Operations Expenses						
	MATE Registration fee	MATE Registration Fee	Purchased	$ 450.00	$ 450.00	$ -
	MATE Registration fee	3 hotel rooms/3 per room, @ 3 nights, 2 nights on the road	Purchased	$ 2,067.00	$ 2,379.37	$ (312.37)
	Fluid Power Quiz Fee	Required	Purchased	$ -	$ 25.00	$ (25.00)
	Props	Misc PVC Pipes	Purchased/Reuse	$ 100.00	$ 27.79	$ 72.21
	Team Merchandise	Polo Shirts	Purchased	$ 661.60	$ 634.53	$ 27.07
	Space Rental	Dive Time at Pool	Purchased	$ 500.00	$ 21.91	$ 478.09
Total Operational Expense				**$ 3,778.60**	**$ 3,538.60**	**$ 240.00**
Total Project Variance				**$ 16,477.76**	**$ 7,158.71**	**$ 9,350.83**

Funding Sources

Funding Sources	Amount
EEF Grant	$2,604.52
SOAC Grant	$4,278.60
EEF Symposium Award	$100
Individual Contributions	$175.59
Total funding	**$7,158.71**

Cost accounting

Very few items were re-used as we were creating an entirely new product. The thrusters were left over from a third sub, and the PVC pipes were left over from past years of MATE prop builds. The DVL is an industrial grade sensor that the club has used since 2019, and is able to provide us with detailed sensing information.