Design Review of the Autonomous Underwater Vehicle *Douglas* by McGill Robotics

Ben Hepditch, Celina Belleville, Barry (Ze) Zhang, Elie-Dimitri Abdo, Felipe Potenza, Alois Luong, Caileigh Bates, Larissa Azzopardi, Alexandre Hafemeister, Anthony Tan, Antoine Dangeard, John-Paul Chouery, Sam Faubert, Andrew Kan

***Abstract*—The McGill Robotics Autonomous Underwater Vehicle (AUV) Team presents Douglas, a completely redesigned AUV that our team developed during the 2023-2024 scholastic year. Douglas features an entirely new mechanical body consisting of a hull, chassis, grabber, and dropper mechanism. Our electrical team has produced a refined version of Clarke's internal electrical architecture with brand new components, including a new power distribution board, custom-designed display, and actuator boards. The software team greatly expanded our core autonomous functionalities, including a more precise navigation algorithm, advanced vision algorithms, and simulation environments. Douglas marks the beginning of a new chapter of innovation for McGill Robotics and our team is proud to showcase its capabilities at RoboSub 2024.**

I. Introduction

Since 2013, it has been the unwavering mission of McGill Robotics to inspire students to build robots and to build robots that inspire students. Over the past decade, the team has developed into an engineering design team at McGill with nearly 200 interdisciplinary undergraduate students split across four unique robotics projects. Between our AUV, UAV, Mars Rover, and business team, our members proudly pour their heart and soul into both the innovation and design of autonomous robots as well as the promotion of robotics and engineering education in the Montreal community. This year, our AUV team worked around the clock to design and manufacture an entirely new addition to the McGill Robotics family of AUVs: Douglas. Every aspect of Douglas was designed and manufactured post-RoboSub 2023. Our mechanical team constructed a more compact and space-efficient hull, complementary chassis, and buoyancy system. Our electrical division designed four new PCBs for regulating the AUV's power, displaying system information on an LCD screen, transforming signals from the three hydrophones, and manipulating the arm. Our software team developed six sophisticated ROS packages with an industry-standard application programming interface (API) for better separation of concerns. Additionally, they developed a hyper-realistic simulation environment using Unity, which enabled the team to test their code well-in advance of the physical AUV's completion. This report details our team's approach to achieving success at RoboSub 2024 with Douglas and covers our strategy for the course, vehicle design, and testing.

II. Competition Strategy

A. Course Strategy

McGill Robotics' course strategy employs the "separation of concerns" (SoC) software design principle with the AUV's decision-making software, referred to as the "planner", which is responsible for guiding Douglas through the course. All decisions made by the planner work under the assumption that the AUV's environment is entirely observable as a discrete set of objects; each with a position, orientation, confidence, and object-specific attributes. Moreover, the AUV's actuators (ie, grabber, dropper, and torpedoes) are made to be controllable through an API which provides high-level navigation logic (i.e. "go to this position", "close the grabber", "drop the marker", etc.).

The planner itself is structured as a state machine, where each state represents a predefined set of instructions (for example, the "Trick" state simply makes the AUV rotate twice around its X axis), or the state can itself be a state machine. This recursive state machine architecture allows the team to program the AUV's behavior at a very high level, with states then being broken down into lower level actions, until they represent very simple instructions.

The assumption of a robust and accurate perception system, which we have created with our design, is essential for our competition strategy. Under this assumption, we're able to decouple our mission plan from the rest of our software stack, which grants us a high-degree of flexibility when implementing our course strategy. This separation of concerns ensures that changes or improvements to the perception system can be made without necessitating modifications to the mission logic and enables our team to develop and test each system independently.

1) Rough Seas and Enter the Pacific

The team will attempt the coin flip using a vision-based mapping system that locates the gate without needing it in the immediate FOV. The planner starts by yawing in place, sweeping the front camera to map the position, label, and orientation of nearby objects. Once the gate is mapped, the AUV stops spinning, moves in front of the gate, performs two rolls for style points, realigns, and passes through with a fixed heading. Instead of using color detection to decide which side to pass through, the AUV will follow pre-coded instructions to go through either the left or right side of the gate, utilizing knowledge available before the competition.

2) Hydrothermal Vent

Similarly, our approach to the buoy task makes use of the observability of objects in the pool provided by the perception software. Assuming the AUV approaches the buoy head-on via path indicators or a pinger, the front camera detects and registers the buoy's position. The AUV then rotates to face the buoy, positions itself 1 meter away for optimal depth accuracy, and follows pre-coded instructions to circumnavigate the buoy. These instructions are designed to be fast while maintaining a safe radius to avoid collision. The direction of rotation (clockwise or counter-clockwise) is also pre-coded.

3) Ocean Temperatures

The bins task relies heavily on the perception stack. Our approach splits the two colored "sub-bins" in two. Each of these colored bins will be given its own position estimate by the perception stack. Thus, the planner will simply center itself above the bin that has the desired color, lower itself until it is right above the bin's z position, and drop the marker.

4) Mapping

After assessing the benefits and risks, the McGill Robotics team decided not to attempt the torpedoes task this year due to limited resources, task complexity, and a low points-to-work ratio. The mechanical team could build only one actuator, opting for a grabber to attempt the high-point "Ocean Temperatures" and "Collect Samples" tasks. The torpedoes' numerous moving parts, software calibration, and overall complexity were not considered worthwhile relative to the points possible, allowing the team to focus on more rewarding tasks instead.

5) Collect Samples

For the sample collection task, we will use the downward-facing camera to locate each of the three samples. The grabber will then place the samples into the bins. The grabber features current sensing capabilities which will confirm whether it has successfully secured a sample.

6) Path and Pinger

The path and pinger tasks serve as navigational aids. When a path indicator is expected, the AUV searches the floor with its downward-facing camera, moving in an expanding circle. Upon detecting the path indicator, the AUV aligns with its direction and moves straight to find the next task, choosing the direction pointing away from the previous task. The pinger's location is determined by three hydrophones under the AUV, providing a constant direction estimate. The AUV follows this direction until the perception stack detects the next task.

B. Team Success Strategy

Focus was placed on ensuring that the components which are brought to competition are as robust to failure as possible. In 2023, the McGill Robotics AUV suffered a broken front camera, a fried power board, several popped fuses, and mechanical failures leading to leaks and water damage in the weeks leading up to competition.

This forced the team to scrap the original vision-based software strategy and fall back on dead reckoning-based navigation. Thus, in engineering Douglas, our team placed reliability as our number one priority.

To this end, numerous design reviews were organized to scrutinize electrical and mechanical designs before implementation. Multiple prototypes of subsystems were created to further guarantee requirements were met. From a software perspective, extensive continuous integration and deployment (CI/CD) pipelines were implemented which guaranteed faulty code would not be deployed on the robot throughout development. Perhaps most importantly, from start to finish, our team was relentlessly focused on insisting on the highest standards. To deliver a brand new design in only 12 months, our team knew we had to hold both ourselves and our designs to the standard required to win at RoboSub.

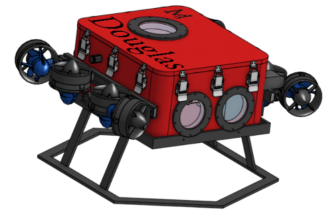

Fig. 1

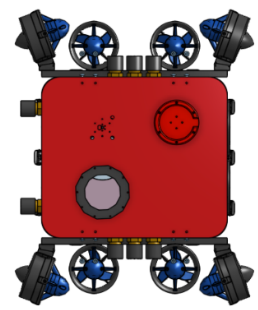

Fig. 2

III. Design Strategy

A. Mechanical Subsystems

McGill Robotics' main design goals this year was to make a small, compact and agile robot, improving the accessibility of the electronics in the hull, and adjusting the center of mass to have a well balanced AUV. Douglas was designed from scratch this year, and the majority of the chassis was constructed using the material from the previous year's robot. This year's team focused on laying a solid foundation for future developments by making a simple and robust robot that can easily be modified and improved.

1) Hull

The hull is rectangular, with a large opening on the top, allowing easy access to the internal electrical systems. This is a change from this AUV's predecessor, Clarke, which had a cylindrical hull with tightly-layered electronics shelves that were difficult to access. The hull has windows on the front and bottom for cameras, and a window on the top to view an electronic board that displays the AUV's system status. The underside of the AUV can be seen in Fig. 2. Throughout the design process, the weight and buoyancy were continuously monitored to keep the AUV's center of mass near the hull's.

2) Design Verification

Finite element analysis confirmed the hull could withstand a depth of 10 m (Fig. 3). The level of deformation produced was minimal and well within acceptable limits, ensuring the hull's structural robustness under the simulated conditions.

To test the effects of the increase in pressure and the quality of the hull's seal, dry ice was used, simulating 1 atmosphere of water pressure with carbon dioxide gas. The amount of dry ice necessary was calculated by using the ideal gas law, and the pressure in the hull was monitored. Any significant loss of pressure would indicate a gas leak. If there is no gas leak, this would indicate a nearly airtight hull which ensures that it will be watertight under similar pressures.

3) Internals

The electronics were secured within the hull using a combination of acrylic and 3D-printed mounts. Each mount underwent multiple design iterations to achieve optimal security, accessibility, and thermal management. The bottom mounting plates and the electronic stack were precision laser-cut from clear acrylic, enhancing visibility for both electronic monitoring and leak inspection (Fig. 14). The batteries were encased in a custom 3D-printed mount and secured with rubber bands, allowing for necessary ventilation. Final positioning of electronic components was strategically planned alongside the electrical team, prioritizing accessibility and optimal weight distribution.

4) Thruster Positioning

The thruster positioning configuration was selected by comparing various potential setups involving different distances, angles, and placements. To determine the optimal configuration, an algorithm and simulations were used to compare the thrust required for various maneuvers (Fig. 4 for evaluations). To secure the thrusters in their optimal positions, custom mounts were designed and machined.

5) Chassis

The team designed the chassis to be as minimalistic as possible while effectively carrying all the task actuators. The chosen material, Aluminum 6061, offers desirable structural and chemical properties suitable for marine applications, allowing for more slender designs and improved hydrodynamics, as seen in Fig. 5. The chassis is attached using screws instead of permanent fixtures to facilitate ease of transportation and future-proofing. Structural integrity is validated through finite element analysis of the inertial forces, as shown in Fig. 6. Task mechanisms are strategically placed on the chassis, below the hull, to remain within the camera's view, avoid thruster wash, and lower the center of mass below the center of buoyancy. Buoyancy is adjusted to +5% using a custom hydrodynamic polyurethane foam topper, and the center of buoyancy is fine-tuned with additional components. The center of mass is balanced with small weights on guide rails, allowing for quick, toolless, and infinitely small adjustments. This fine-tuning of parameters reduces the workload on the thrusters, concentrating power on maneuverability rather than counteracting destabilizing forces.

6) Grabber

To address the dropper and sample collection tasks the AUV is equipped with a single degree of freedom mechanical claw attached to the bottom of its chassis, positioned within the view of the downward-facing camera. This claw was sourced commercially and subsequently modified. It features interlacing fingers to enhance current sensing capabilities, which will be used to detect the resistance from an object and confirm whether the claw has successfully grabbed it. Additionally, an extra layer of rubber has been added to the claw to improve grip. We chose a claw for its versatility, as it can be used for both the dropper task and the sample collection task (Fig. 12).

B. Electrical Subsystems

1) Power Board

The Power Board (Fig. 9) is responsible for powering the different subsystems of the AUV, controlling the eight thrusters, and enabling kill switches. The board features voltage regulators for power distribution, a Teensy 4.0 micro-controller, a dual battery input hot-swap controller, battery voltage sensors, thruster current sensors, water leak detection circuitry, and a two-stage cascaded kill switch (Fig. 7). The main kill switch is used to cut power to the thrusters only, while the secondary kill switch allows for the killing of the whole system in case of emergency. In case of a leak, the micro-controller can also kill the system without requiring physical activation of the system kill switch which we have implemented due to past failures from previous AUV models. An important design consideration was allowing the AUV to be fully functional with a single battery, enabling a second battery input aimed to extend how long the AUV could operate in a single mission if needed. All current and voltage information is relayed through ROS to the Jetson and other embedded systems in the AUV.

2) Display Board

The Display Board (Fig. 9) is made using an ILI9341 display and is controlled by a Teensy 4.0. The screen and the Teensy communicate using the Serial Peripheral Interface (SPI) communication protocol. It was developed to help us visualize what is currently happening with the different subsystems and monitor our batteries discharging. It is located directly under the top side circular window for easy visual inspection. The Display Board displays critical information on its screen, such as the voltages of both batteries, the position and orientation of the AUV, the depth, as well as the status of each thruster, doppler velocity log

(DVL), inertial measurement unit (IMU), cameras, and other boards.

3) Actuator Board

The Actuator Board features an onboard Teensy 4.0 microcontroller that is responsible for controlling the servo motors used in the grabber, dropper, and future torpedo subsystems (Fig. 11). It can support up to 5 servo motor outputs and features servo current sensing circuitry. Additionally, the board has 1A fuses for each servo and status LEDs. The Teensy communicates with the Jetson via ROS to send current sensing data and receive servo actuation commands.

4) Hydrophone Board

The Hydrophone Board utilizes an STM32 Nucleo microcontroller to process signals received through the four external hydrophones. The hydrophones are connected to a filter amplification board that processes the pinger signals being measured by the analog pins on the STM32. The microcontroller employs a Fast Fourier Transform (FFT) algorithm to compute the frequency of the incoming sound waves and also saves the timestamp each hydrophone receives the signal. The frequency of the incoming sound wave and time differences between the hydrophones are relayed to the Jetson through ROS, enabling it to triangulate the position of the pingers relative to the AUV.

C. Software Subsystems

The AUV's software architecture comprises several Robot Operating System (ROS) Noetic packages, each containing multiple Python3 and C++ processes. These packages communicate through ROS middleware topics and services. An on-board Jetson AGX Orin provides the necessary computational power to run all packages concurrently within a Docker container. The ROS packages are categorized into four main groups: sense, plan, act, and sim. Sensing is handled by sensor drivers, state estimation, and vision packages. Each sensor driver is encapsulated in a ROS node, interfacing with physical sensors using specific low-level protocols: I2C and ROS serial for the depth sensor, USB for the IMU, and UART for the DVL. These nodes output measurement vectors, which are consolidated by the state estimation package. An Extended Kalman Filter then processes this data along with the latest state estimate to determine the AUV's current pose with covariance.

The vision package interprets the environment using front-facing and stereo cameras. Both feeds utilize a fine-tuned YOLO-v8 model for object detection. For the downward-facing camera, state estimation and camera intrinsics data help calculate direction vectors to detected objects, enabling rough positional estimates on the pool floor. The front-facing stereo camera generates a depth map, which, combined with state estimation data, produces a 3D point cloud. Object detections are then contextualized within this point cloud to infer 3D positions.

Planning is managed by a dedicated package that employs a state machine algorithm. It utilizes data from state estimation and vision to determine the next action. Each possible competition run state is assigned a corresponding function, which can dispatch actions to the controls package and monitor progress. State transitions are determined based on action outcomes. The controls and propulsion packages ensure precise AUV movement. The controls package receives goal positions and orientations, employing multiple PID loops to generate body-framed forces and torques. The propulsion package then decomposes these forces and torques into thruster PWM speeds, which are communicated to the ESCs via a ROS-serial node.

Comprehensive testing is facilitated by a custom Unity simulation environment that replicates the competition setting and mimics all sensor and camera data. This allows for bug testing, vision model training, and competition run simulations. Additionally, a continuous integration pipeline performs regular automated tests to maintain code integrity.

IV. Testing Strategy

Our testing strategy was composed of two main categories: pool tests and dry-tests. Overall, these two categories fit into an iterative approach in which new designs were first tested at the component level, then at the sub-system level, and finally at the full system level. At each stage, clear success criteria is defined and data was extracted to validate the results. The three phases of testing are broken down as follows:

1) Component-level tests are the first tests after a new design is finalized. The purpose of component tests is to identify errors in the new design as an isolated unit before they're integrated into any other existing system. For example, before integrating any electrical equipment into our hull, our mechanical team conducted a series of tests to validate the waterproofing of the design.
2) After passing the component phase, all of our designs were connected to a smaller subsystem of Douglas to ensure there were no issues with their integration. For example, to perform a sub-system test of our display board, our electrical team benchmarked the voltage and current outputs of our power and compared the outputs on the display board given the same tested inputs to validate the data transmission.
3) Finally, once an entire sub-system is validated, it is integrated into the overall AUV, at which point full system tests can be performed. Continuously integrating and developing our systems in this manner enables us to quickly identify issues that arise without having to check the entire system each time unexpected behavior occurs.

V. Conclusion

The development and implementation of ”Douglas” represents a culmination of relentless dedication, innovation, and collaboration within the McGill Robotics AUV team. From the inception of the project in September 2023 to its realization, every aspect of Douglas's design, development, and operational capabilities has been meticulously crafted and refined by a group of talented students at McGill Robotics.

Douglas features an entirely new mechanical body consisting of a hull, chassis, grabber, and dropper mechanism that complemented with electrical's new internal electrical architecture with brand new components, including a new power distribution board, custom-designed display, and actuator boards. This is all greatly aided by our expanded core autonomous functionalities, including a more precise navigation algorithm, advanced vision algorithms, and simulation environments.

The collaborative efforts of our multidisciplinary team, spanning mechanical, electrical, software, and vision and simulation domains, have resulted in the development of cutting-edge algorithms and systems that enable Douglas to accurately identify and interact with objects in its environment. The testing and validation procedures undertaken throughout the design process ensure Douglas's reliability and effectiveness in real-world deployments, culminating in successful field tests and validation experiments.

We look forward to showcasing Douglas's capabilities at RoboSub 2024, where we are not only demonstrating the technical excellence of our AUV but also the passion and commitment of the McGill Robotics team to inspire innovation and engineering education.

REFERENCES

[1] Glenn Jocher, Ayush Chaurasia, and Jing Qiu. *Ultralytics YOLO*. Version 8.0.0. Jan. 2023. URL: https://github.com/ultralytics/ultralytics.

ACKNOWLEDGMENTS

The McGill Robotics AUV team is grateful for all the support and encouragement from organizations and individuals without them our achievements would not be possible. We extend our heartfelt thanks to our sponsors for their generous contributions and unwavering support. These include the Engineering Undergraduate Society (EUS), the Students' Society of McGill University (SSMU), the Sustainability Projects Fund (SPF), McGill24 donors, Nissan, uMake, CMEquip, Multi Caisses, Robotshop, Sial, HPRC, Metal Pros, Movella, and the McGill Faculty of Engineering. We also express our gratitude to McGill University for facilities and support which have been critical to our project's success. Additionally, we thank those associated with facilitating our pool tests at the McGill Memorial Pool and other locations. We would like to acknowledge the hard work and dedication of all our team members. Finally, we would like to thank RoboSub for hosting and creating a competition that brings together teams from around the world to compete and collaborate.

APPENDIX A
COMMUNITY OUTREACH

McGill Robotics' mission is to inspire students to build robots and to build robots that inspire students. We believe it is important to give back to the community which is why we are an organization that advances the field of robotics while also nurturing a community that values sustainability, collaboration, and education. One of the most significant events organized by McGill Robotics is its annual hackathon, RoboHacks, which brings together high school, College of General and Professional Teaching (CEGEP), and university students. This event is more than just a competition; it is an opportunity for students to collaborate, innovate, and practice design processes. RoboHacks emphasizes sustainability, encouraging participants to create solutions that are not only technologically advanced but also environmentally friendly. In addition to volunteering at McGill Robotics events, such as Robohacks, members of our AUV team take the time to give back to the community. We have a few members that volunteer with S.W.A.M. (Swimming With A Mission), a non-profit organization dedicated to providing affordable and accessible one-on-one swimming instruction to children with disabilities. Finally, we have formed a connection with a local school, Trafalgar, and have helped them implement more STEM into their curriculum. Our team has spent time in classrooms assisting students and teachers using 3D printing as a method to learn about design processes. We look forward to helping them start up a robotics club in fall 2024.

Appendix B
Design Verification

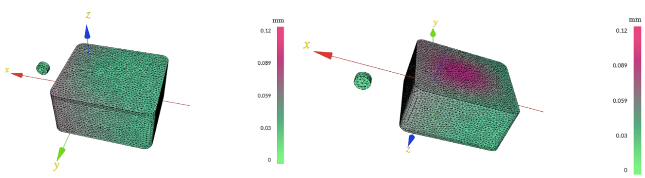

Fig. 3

Appendix C
Thrusters Layout

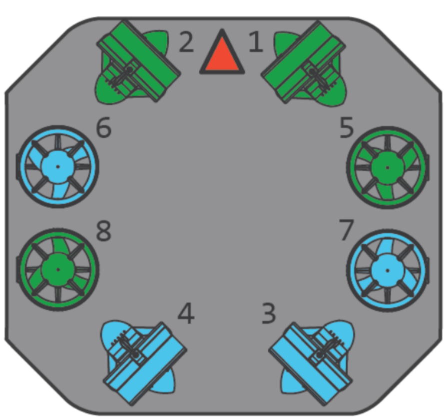

Fig. 4

Appendix D
FEA Diagram Leg

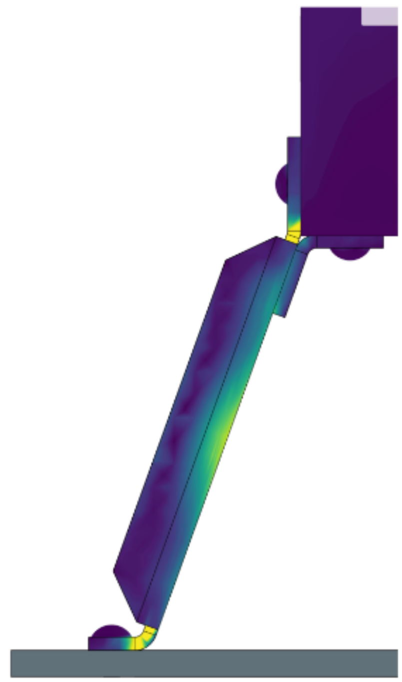

Fig. 5

Appendix E
FEA Diagram Hull

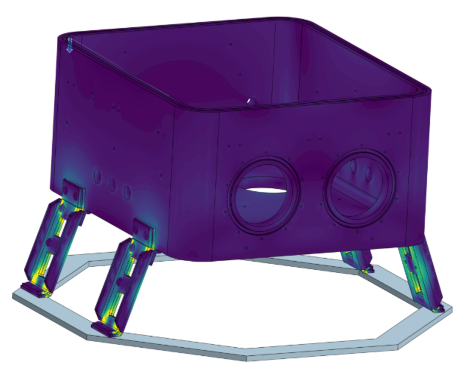

Fig. 6

Appendix F
Kill Switch

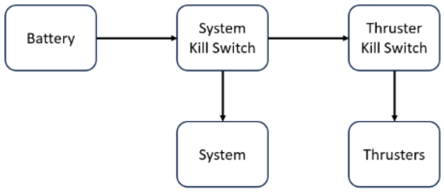

Fig. 7

Appendix G
Power Board

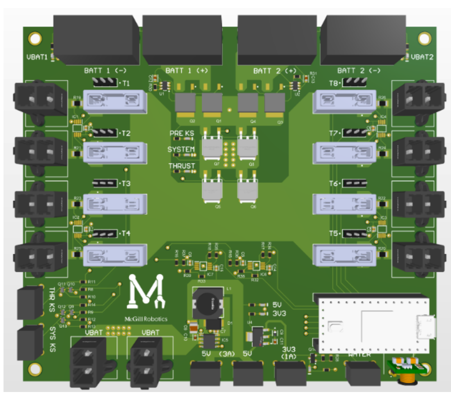

Fig. 8

Appendix H
Display Board

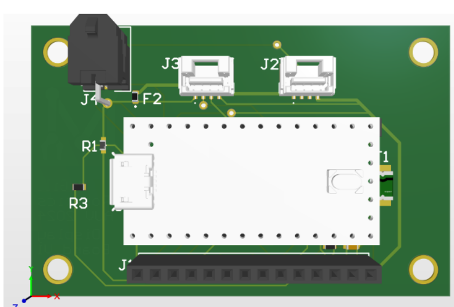

Fig. 9

Appendix I
Pressure Sensor Board

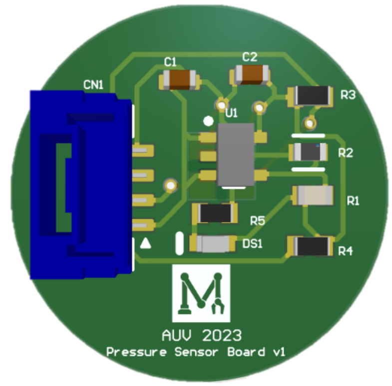

Fig. 10

Appendix J
Actuator Board

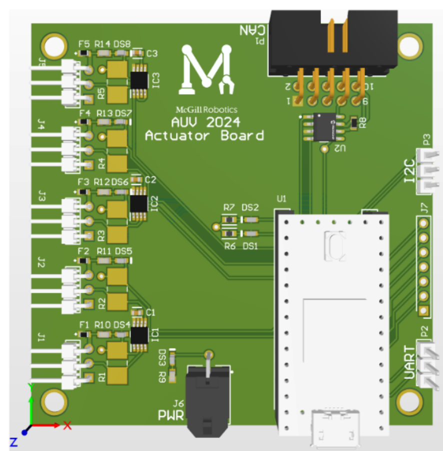

Fig. 11

Appendix K
Grabber

Fig. 12

APPENDIX L
PRESSURE TESTING

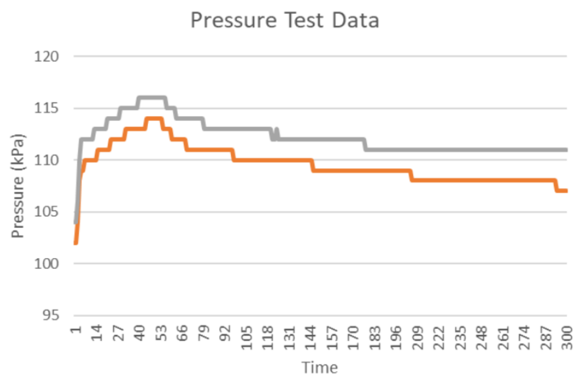

Fig. 13

APPENDIX M
AUV INTERNALS

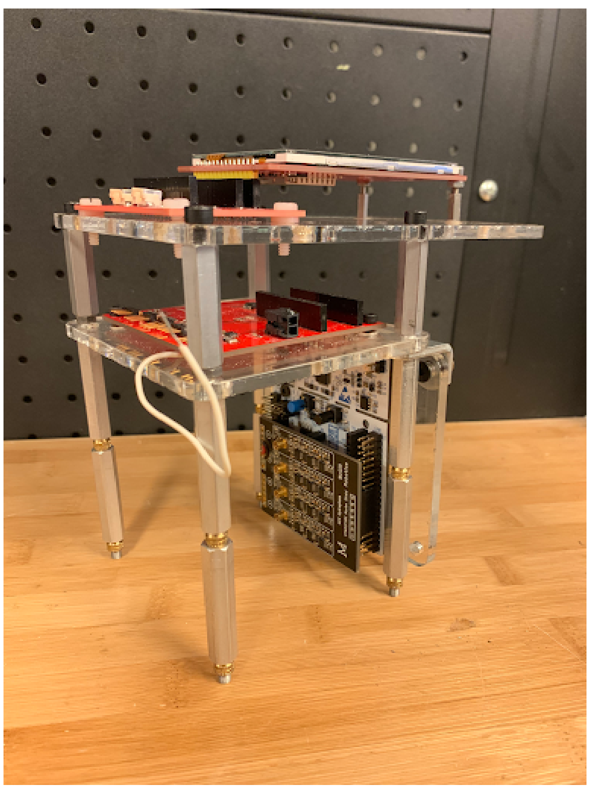

Fig. 14

APPENDIX N
SOFTWARE ARCHITECTURE

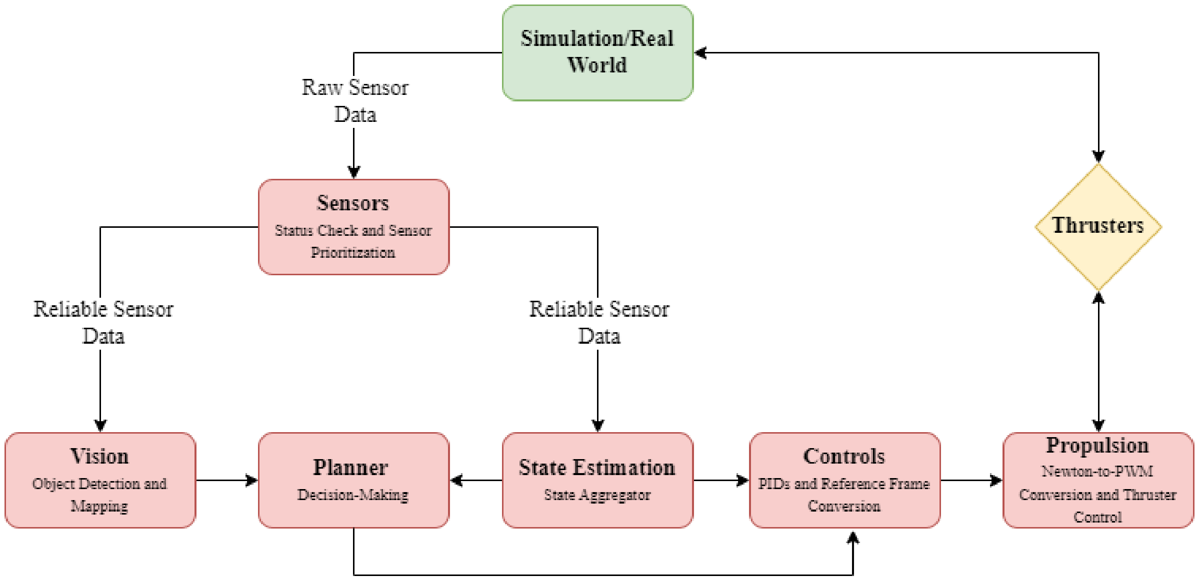

Fig. 15

APPENDIX O
PLANNER FLOWCHART

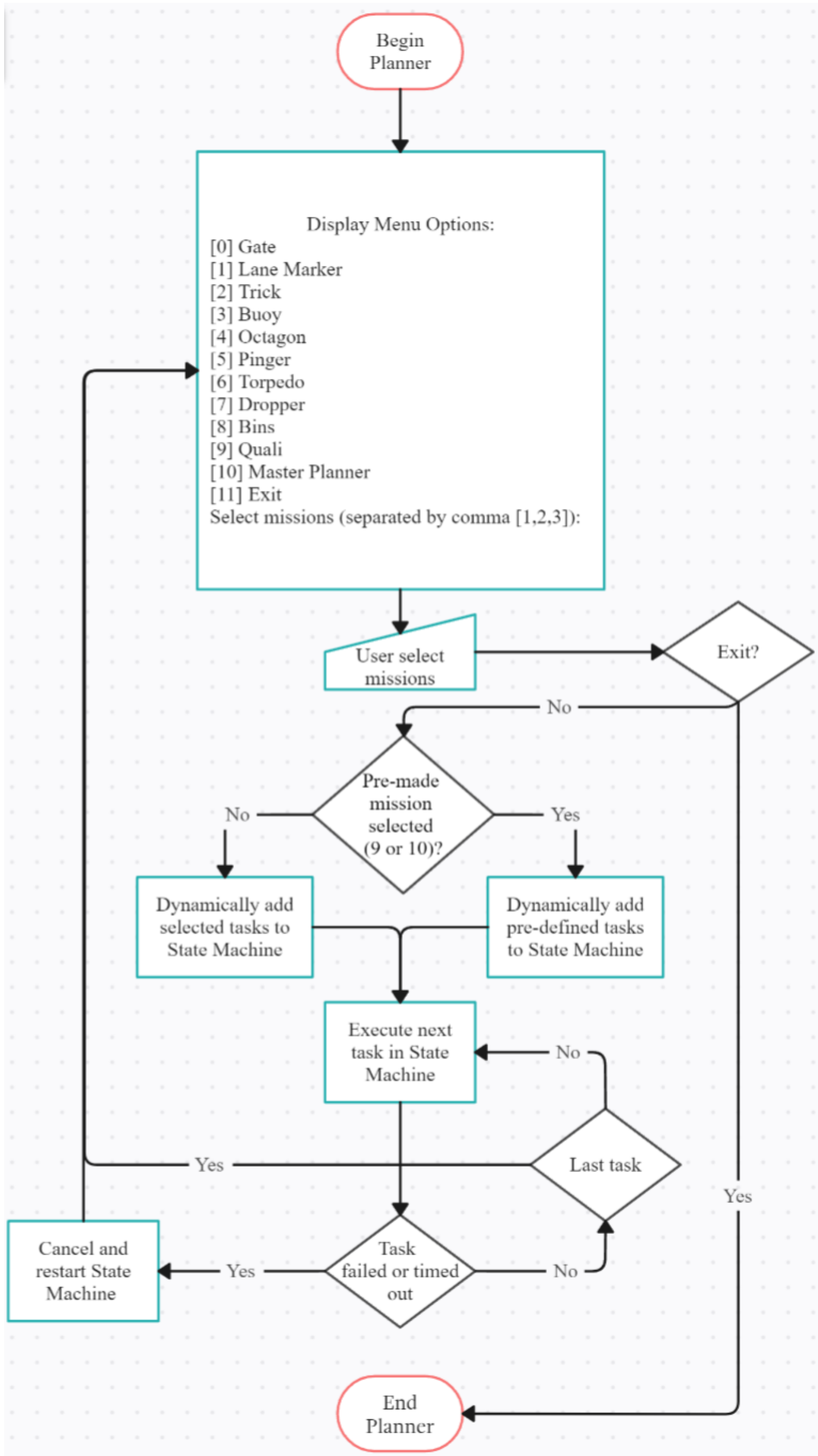

Fig. 16

APPENDIX P
VISION FLOWCHART

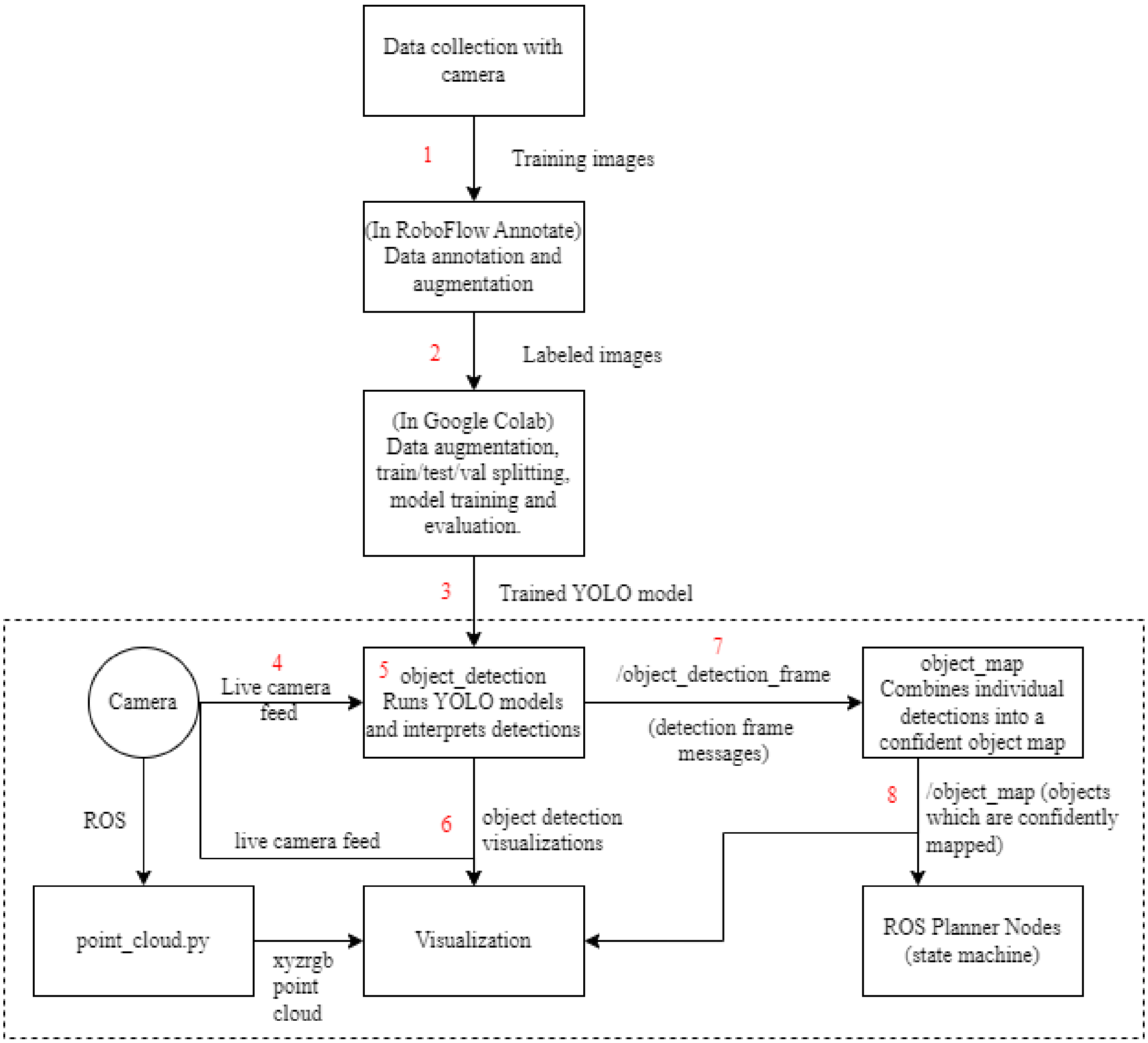

Fig. 17

APPENDIX Q
COMPONENT LIST

Components					
Component	Vendor	Model/Types	Specs	Custom/ Purchased	Cost
Thrusters	Blue Robotics	T-200	——	Purchased	——
Hull	——	Custom Aluminum Milling	——	Custom	$2,500
Chassis	——	Custom Aluminum Cut and Bent	——	Custom	——
Internal Electronic Mounts	——	3D Printed	——	Custom	——
Internal Mounting Plates	——	Custom Laser Cut Acrylic	——	Custom	——
Foam	Blue Robotics	Custom Milled	——	Custom	$160
Actuators / Manipulators	Amazon	——	——	Custom	$30
Waterproof Connectors	——	——	——	Purchased	——
Waterproof Servo	——	——	——	Purchased	——
LiPo Battery	——	——	——	Purchased	——
ECU	NVIDIA	Jetson AGX Orin	——	Purchased	$2000
IMU	SBG Systems	Ellipse-N	——	Purchased	Sponsored
Front Camera	Stereo Labs	ZED 2i Stereo Camera	——	Purchased	$738
Down Camera	Amazon	Camera USB-USB500W02M	——	Purchased	$70

Hydrophones	——	——	——	Purchased	——
Pressure Sensor	——	MS5837-30BA	——	Purchased	Sponsored
DVL	Waterlinked	DVL A50	1 MHz	Purchased	$7600
Window Polycarbonate	McMaster Carr	——	——	Purchased	$9.30
System Kill switch	Blue Robotics	——	——	Purchased	$50
O-rings	McMaster Carr	——	——	Purchased	$50
Latches	McMaster Carr	——	——	Purchased	$168
Claw	Amazon	——	——	Purchased	$28
Epoxy	Canadian Tire	——	——	Purchased	$200
Aluminum Window Covers	——	Custom Aluminum Milling	——	Custom	$300
O-ring Grease	Amazon	KEZE	——	Purchased	$18
Internal Component Securement	——	Custom 3D printed	——	Custom	——
Main Thruster Kill Switch	——	Custom 3D printed	——	Custom	——
Alumnium 6061 Stock	——	——	——	Purchased	——
Buoyancy Foam	Blue Robotics	——	——	Purchased	$160
Power Board PCB	——	Custom PCB	——	Custom	——
Pressure Sensor PCB	——	Custom PCB	——	Custom	——
Hydrophone Board PCB	——	Custom PCB	——	Custom	——

Display Board PCB	——	Custom PCB	——	Custom	——
Actuator Board PCB	——	Custom PCB	——	Custom	——
MCU	PJRC	Teensy 4.0	——	Purchased	——
MCU	STMicro-electronics	STM32-L433RC	——	Purchased	——
Data Processing	Roboflow	——	——	——	——
Computer Vision Model	Ultralytics	YOLOv8	——	——	——
Open Source Software	——	ROS, PyTorch, OpenCV	——	——	——
Planner Algorithm: Behavior-Tree	——	smach	——	——	——
Software Environment Management	Docker, GitHub, GitLab	——	——	——	——
Simulation Environment	Unity, Gazebo Ignition	——	——	——	——