RobotX 2024 Technical Design Report

MARVL Lab, Singapore University of Technology and Design

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***Abstract*—This paper highlights the contributions of Team MARVL from Singapore University of Technology and Design for the RobotX 2024 competition. We provide a low-cost real-world framework for validating the tasks for RobotX. Specifically, we propose platform agnostic algorithms for object detection and goal localization which can be foundational tools for solving tasks 3,4,5,6 in RobotX. We validated our proposed perception and localization modules for these respective tasks using MARVL's BlueBoat .**

I. COMPETITION STRATEGY

Our logistics to procure/loan a WAM-V[12] for Robot-X[9] unfortunately did not succeed, hence we are unable to participate with hardware this year. However, we did develop several software modules and tools that are platform agnostic and can be readily useful for implementing them on WAM-V in the future. We validated our proposed software contributions using a customized version of Blue Robotics' Unmanned Surface Vehicle (USV). We refer to this modified version as MARVL's BlueBoat[11]. In addition, we also generated 3D CAD models for payload and sensor mounting on BlueBoat as well as WAM-V.

A. Testing Vehicle

BlueBoat is an USV manufactured by Blue Robotics, which is meant for conducting marine surveys. We mounted LIDAR and Camera with its respective electronics on the BlueBoat, as shown in Fig. 1, using a custom payload tray. This allowed us to test our algorithms and sensors in small space like swimming pool and simulate Robot-X tasks, and then transition to WAM-V. We plan to continue using this setup for development even after procuring our WAM-V, as it can significantly reduce validation and test time on WAM-V.

B. Strategy

For perception, we propose a sensor fusion pipeline which integrates 3D LIDAR point cloud data with camera. In addition, we use advance computer vision and machine learning techniques for object detect and 3D localization of target objects. The outcome of this module can be used as inputs to the controller for RobotX Tasks 3,4,5,6. We also integrated this module a 3D SLAM algorithm to simultaneously localize and map the environment for these tasks.

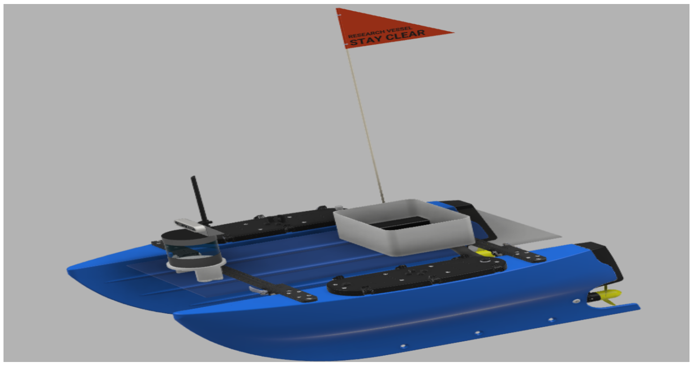


Fig. 1: 3D Model of the MARVL Blueboat

II. DESIGN STRATEGY

A. Mechanical Design

1) MARVL ASV(Autonomous Surface Vehicle): We generated 3D CAD models for WAM-V to retro fit the platform with enhanced sensors and propulsion systems. Our plan is mounting two thrusters with batteries on both side for stability. All the electronics will be enclosed in a Pelican[8] Water Proof Case with separate mounts for Camera and LIDAR in front of the payload tray as shown in Fig. 2.

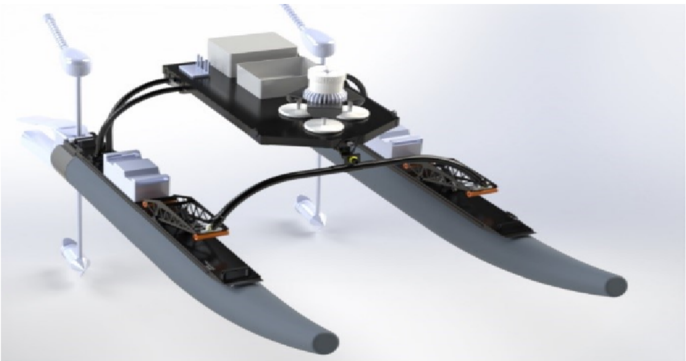


Fig. 2: 3D Model of the MARVL Team's WAM-V

2) LIDAR Mount: We use a Robosense-RS 128 [10] LIDAR for ego-vehicle localization as well as surrounding objects. Our design team generated mount designs for both

WAM-V as well as BlueBoat according to their respective constraints. The mounts for WAM-V can be fabricated using a combination of sheet metal and 3D printed parts, which can be mounted onto the payload, while the Blueboat mounts were 3D printed. Figs. 3 and 4 illustrates the same.

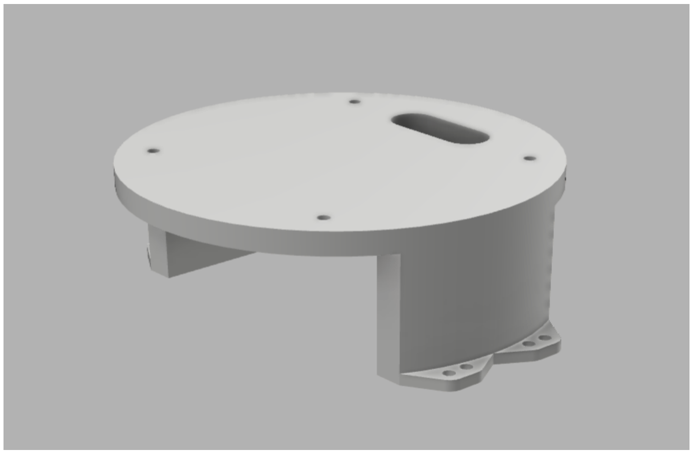


Fig. 3: Blueboat LIDAR Mount

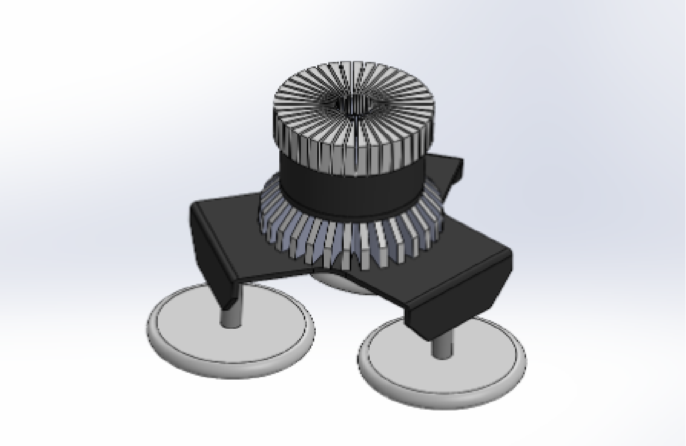


Fig. 4: WAM-V's LIDAR Mount

3) Camera Mount: Given the need for the WAM-V to detect colour sequences quickly and perform object detection at a distance, we plan to use the FLIR Blackfly S Camera [4]. This camera offers high image quality and enhanced colour detection capabilities, making it well-suited for these tasks.

We use Intel RealSense D455 Camera [2] for the BlueBoat due to our constraints to procurement of BlackFly S camera. However, it is still a good choice due to its long range clarity and also the option of using depth sensor, if required. The mounts for it are also 3D printed (refer Figs.5 and 6) and placed exactly on top of the LIDAR for easier inter-sensor calibration while performing sensor fusion.

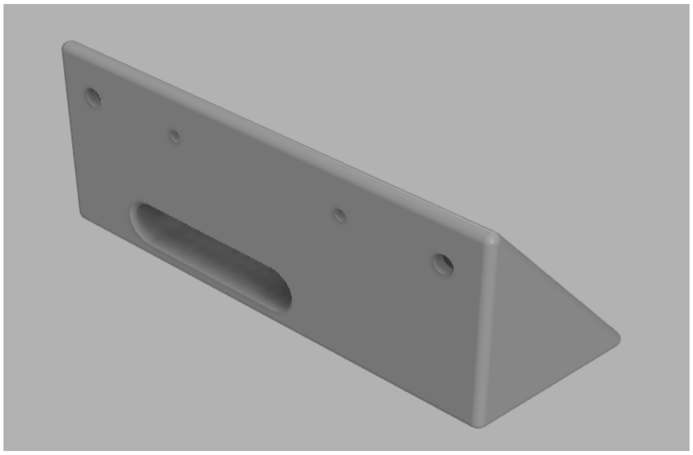


Fig. 5: Blueboat Camera Mount

Fig. 6: WAM-V's Camera Mount

4) Electonics Hull/Box: The ASV's main electronic hull structure is a Pelican case, which contains the computer, flight controller, and power subsystems. It is secured with ratchet straps, providing both easy access for maintenance and a reliable, stable connection. The Blueboat's electronics case is a plastic case drilled on the acrylic payload tray of the tray. It includes the computer with its battery, a buck converters, and the connections to the LIDAR and camera. Fig. 7 and Fig. 8 present the electronic casings.

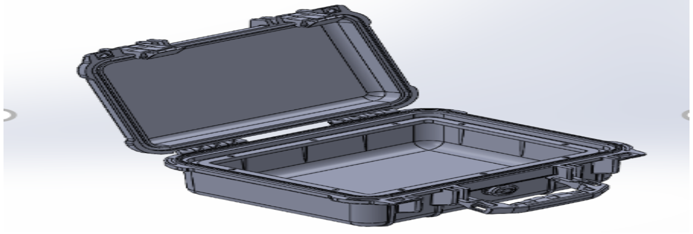


Fig. 7: WAM-V's Pelican Box

5) Ball Shooter: The ball shooter mechanism is inspired by the tennis ball shooters. The ball is loaded into the shooter with a slider crank mechanism which allows the ball to fall into the shooter and subsequently pushes it toward the rapidly rotating flywheels. Upon contact, the flywheels accelerates the ball rapidly, launching it forward. The ball shooter is mounted on a

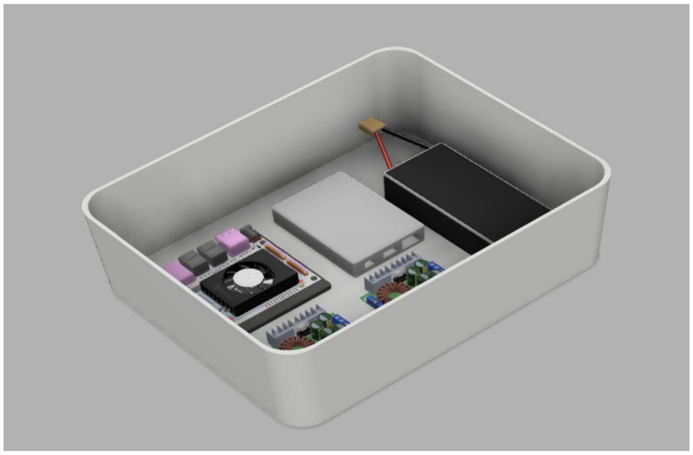


Fig. 8: 3D render of BlueBoat's Electronics Box

3-axis base with pitch, roll and yaw axes for aiming. The yaw is controlled by a brush-less DC motor with a gear reduction from the gear to the base, allowing for more torque in moving the shooter. Similarly, the pitch axis is controlled with 2 brush-less DC motors with a gear reduction through a timing belt. Finally, the roll axis is controlled by the same motors controlling the pitch axis through a differential mechanism, as illustrated in Fig. 9.

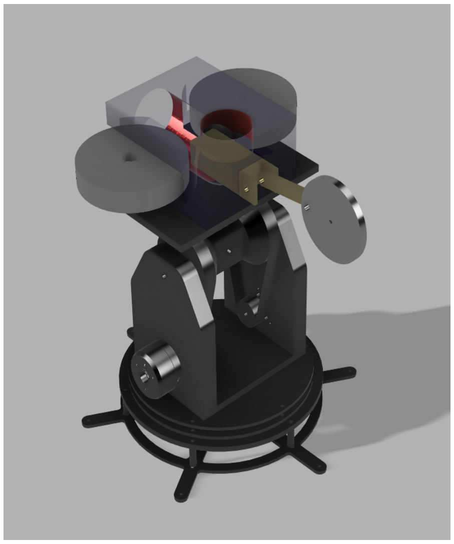


Fig. 9: Ball Shooter Mechanism

B. Electrical Design

1) Electrical Architecture: The planned electrical system of our WAM-V uses a single hull to simplify the system. The overview of the system is presented in Appendix B. The hull contains the computer to control the craft as well as the power conversion modules. The antennas, electronic speed controllers and batteries are to be placed outside of the hull to ensure electrical isolation and reduce electrical interference between them. The BlueBoat uses a much simpler electrical system with 19 and 12 volt branches powering the NVIDIA Xavier[3] which (can be given 9-20V input) and our LIDAR. Other components such as the camera are powered from the Xavier's USB outputs.

2) Control Architecture: The user can communicate with the WAM-V through two separate wireless interfaces. The data link uses an ubiquity antenna to provide heartbeat data and information through Robot operating system (ROS) [15], while the kill switch is provided by a RC transmission using ExpressLRS [17], a long range and reliable system used in drones. For the BlueBoat, we use a simple arm/disarm mechanism using ArduPilot[16] which is interfaced by using MAVROS[14], helping us achieve remote kill capability which is a requirement by RobotX. Our plan is to implement it for the WAM-V in the future.

3) Power Distribution: The Torqueedo batteries provide about 25.2v nominal voltage, which is be stepped down to 24v, 12v and 5v as necessary using respective buck converters. These are chosen due to their high efficiency and small size, allowing for a reduction in temperature within the hull. The emergency E-stops are planned to be connected to the main on-off switches to directly cut the power to the thrusters, again a mandatory requirement of the Robot-X. For a low-cost validation, we implement a miniature version of this system for the BlueBoat as shown in Fig. 10.

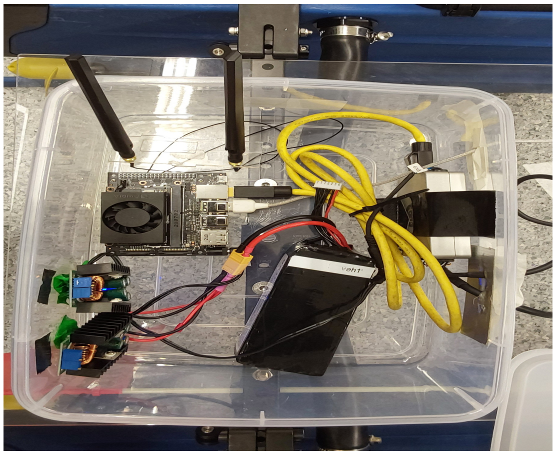


Fig. 10: BlueBoat Electronics box

C. Software Sub-System

1) Software Architecture: Our proposed software architecture is shown in Fig. 18, in Appendix B includes doing LIDAR and Camera data fusion with object detection using machine learning algorithms. Our object detection module is combined with 3D LIDAR data to detect objects and localize them. We also combine the sensor fusion data with data from GPS and IMU to localize our boat. This information is sent to our mission planner which decides our plan and sends to our control algorithms for motor movement. We use LIDAR for its rich point cloud information which is required to get information for small objects like buoys in the arena. Our later testing however did find out that using such a power-heavy LIDAR has its own issues as it slows down our computer to do fusion in real-time, hinting to look for alternative lighter LIDARs. We used ROS for building our middleware for our proposed software architecture.

Fig. 11: Perception Hardware

2) Vision: We implemented YOLO v5 [6] for performing object detection for various target detection related RobotX tasks. This includes the circular and conical buoys in different colours. The object detection is performed real-time on a NVIDIA Jetson Xavier NX using cuDNN and tested in our pool trials using the BlueBoat. During the validation process, we observed that our trained object detection model repeatedly gave us false positives for some specific buoy classes. This was due to imbalanced dataset classes. Upon performing data augmentation on classes which were underrepresented, our model became much more balanced and performed better.

3) Control: We used NTU's[13] 2023 VRX competition's control system, which is a longitudinal PID controller which minimized the heading error between WAM-V's current orientation and orientation of line segment joining WAM-V's current position with the goal position by regulating its angular velocity, and an adaptive proportional controller regulates its longitudinal linear velocity based on distance-to-goal and shifts the velocity profile band based on the detected obstacles. The controller was able to perform station keeping in the VRX [1] simulator open sourced by OSRF(Open Source Robotics Foundation)[5].

4) Localization and Mapping: We use 3D HDL SLAM[7] for simultaneous localization and mapping for the tasks in the VRX simulator. Our team is able to implement the SLAM algorithm in the simulator and are currently working on its integration with our controller for VRX tasks. This capability for localization and mapping can be used for several RobotX tasks. Fig. 12 and Fig. 13 show the third perspective view of WAM-V using SLAM algorithm for docking task in the VRX simulator.

Fig. 12: RViz View of Docking Task

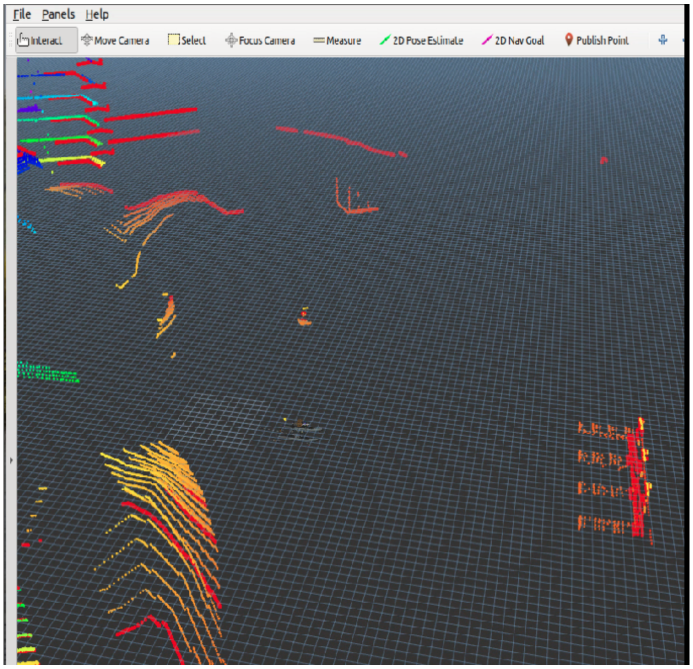


Fig. 13: LIDAR point cloud data for SLAM during docking task

III. TESTING STRATEGY

Our primary testing strategy is divided in two parts:

- Using VRX sim and
- In-field testing using BlueBoat in a swimming pool

We used the VRX simulator for developing our SLAM algorithm for tasks like Docking in the simulator. This is very similar to the RobotX tasks. The second option is another low-cost but a real-world based setup to test our mechanical designs, electronics and software architecture. We deployed our BlueBoat with sensor suite including LIDAR,Camera and on-board computer as the payload. We validated our object detection software modules in a swimming pool where we tried reproducing cones as buoys that are used for competition tasks. This allows us to test the durability and waterproofing of our mechanical mounts.

A. Simulator

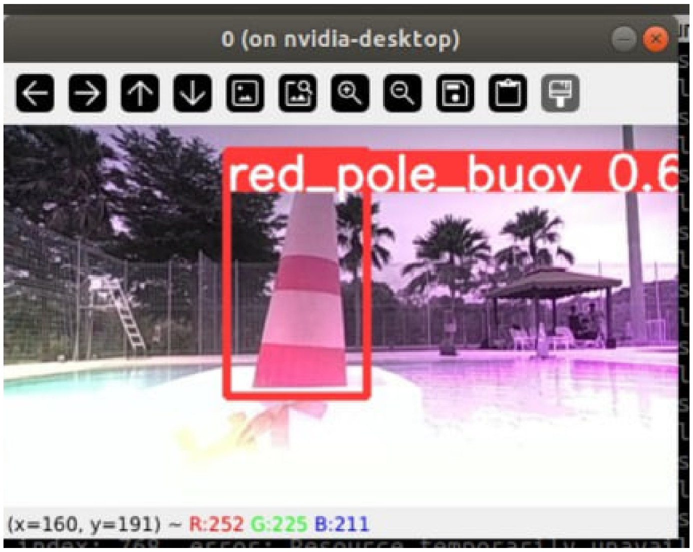
As mentioned earlier, VRX sim serves as our main training and testing interface for the planning and control algorithms. Starting from station keeping and wayfinding, these tasks help us validate the PID controller in action for our requirements. Our team is able to run our SLAM algorithm in simulation. However, we observed that the simulated environments were not rich enough for the SLAM algorithm to localize itself. Also, only dock and deliver were a viable task for using SLAM. Thus simulation testing saved us significant time and cost.

B. Object Detection

We used camera on the BlueBoat to test our object detection module. We used a cylindrical cone to emulate the red buoy from RobotX competition and placed it in the pool for real-world, low-cost validation. We recorded the object detection probability with confidence level around $0.6 - 0.7$ for the red cone. Fig. 14 shows an example outcome from the pool trial with shadowed lighting condition. This pointed towards us the fact we have to make changes in our dataset to include more images of target objects in low-light marine conditions.

C. Camera-LIDAR Sensor Fusion

Our sensor fusion pipeline works using LIDAR with camera. We performed testing using cylindrical cones as alias of cylindrical buoys, which helps us emulate the real case scenario of buoys and other objects in the Robot-X arena. Our sensor fusion approach can be siginificantly helpful for Robot-X Task $3 - 6$ that require the ability to detect target object and its position with respect to the WAM-V in the 3D world coordinate frame. Fig. 15 and Fig. 16 show the outcome of our perception module which is able to detect two different colour cones and their 3D world coordinates with respect to the BlueBoat. Our experimental results suggest that we achieved around 8cm margin of error in both lateral and longitudinal directions. Refer to Appendix C for quantitative results.



0 (on nvidia-desktop)

(x=160, y=191) ~ R:252 G:225 B:211

Fig. 14: Object detection in pool

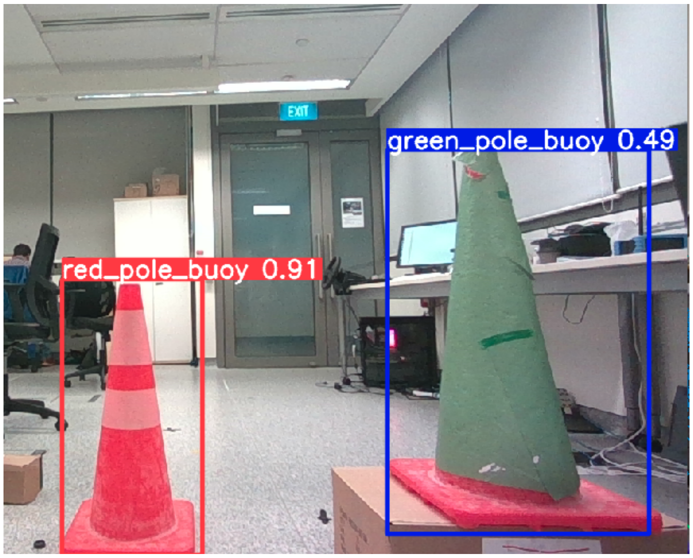


Fig. 15: Multi-target object detection in lab

CONCLUSION

We successfully demonstrated how MARVL's BlueBoat can be a low cost,real world and platform agnostic framework and can be supplemented with the VRX simulator for Robot-X development and testing purposes. It enabled us to continue development even without access to the WAM-V, allowing us to successfully complete the full perception pipeline (Object Detection, Camera-LIDAR fusion) for Tasks 3,4,5,6 in RobotX. It also helped us build mechanical designs for the WAM-V using experienced gained doing it on the BlueBoat, and is a great way of connecting the bridge from Sim(VRX) to Real(WAM-V) without the logistic challenges latter poses, but still providing nearly exact testing conditions and helping achieve high levels of task accuracy.

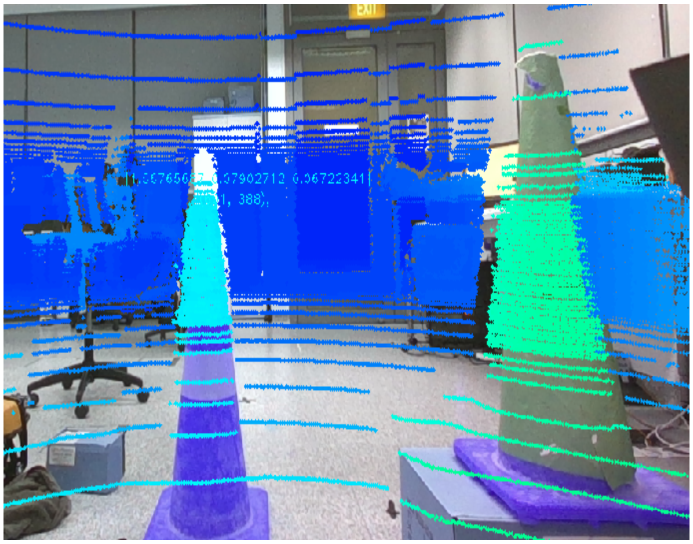


Fig. 16: Camera-LIDAR sensor fusion

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APPENDIX A

Component	**Vendor**	**Model/Type**	**Cost**	**Year of Purchase**
USV	Blue Robotics	BlueBoat	Legacy	2023
LIDAR	—	Robosense 128 RS	Legacy	2023
Camera	—	Intel Realsense D455	Legacy	2022
Batteries	HobbySquare	ONBO 5200 mAh LIPO	Legacy	2023
On-board computer	ELEMENT14 PTE. LTD.	NVIDIA Jetson Xavier NX	Legacy	2023
Buck Converters	—	XL401 6E1	Legacy	2023
GPS	Hobby Square	mRobotics M10034-M9N	Legacy	2023
Flight Controller	—	PixHawk 6C/Navigator	Legacy	2023
RC Controller	—	BetaFPV LiteRadio 3 Pro	Legacy	2023
LIDAR/Camera Mounts	In-House	Custom	—	2024
Object Detection	In-House	YOLOv5	—	—
Sensor Fusion	In-House	Custom	—	—

APPENDIX B

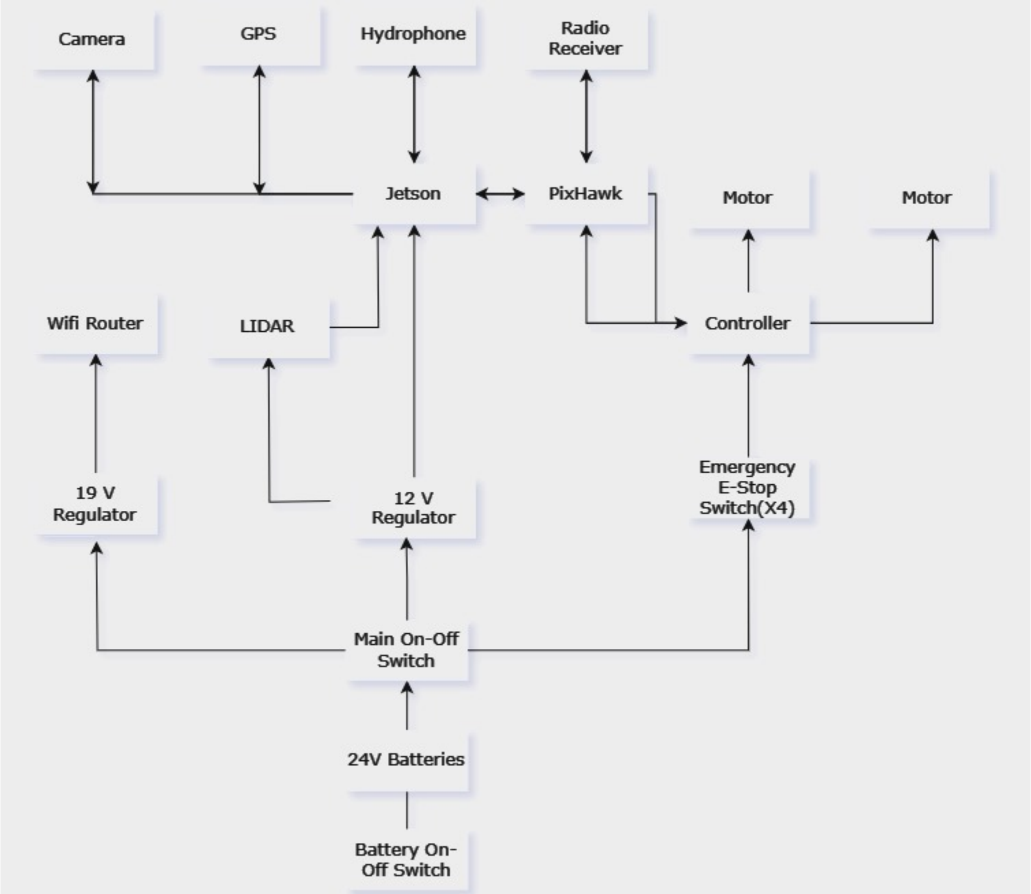

Fig. 17: Power Design System

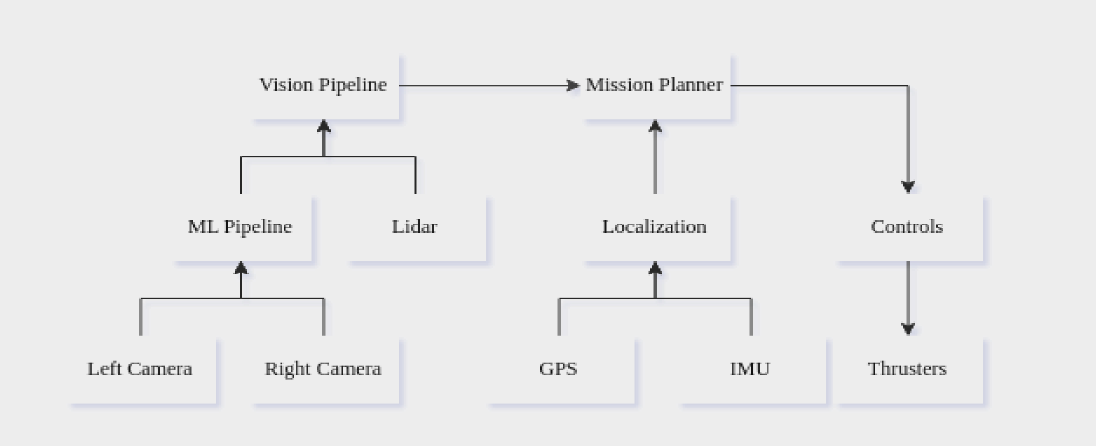

Fig. 18: Our planned software architecture

APPENDIX C

TABLE I: Camera-LIDAR Fusion Results

Dimension	Mean error (in cm)	Standard Deviation in error(in cm)
x	8.1	2.9
y	8.6	7.1
z	8.4	8.2