SAIL-IL's "The Gallili" Autonumous Vessel

TAU SAIL-IL 2021 roboboat competition technical design review

SAIL-IL team, Tel Aviv Univerity, Tel Aviv, Israel

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***Abstract*—This report describes the strategy, decision making and development progress of the 2020-2021 Tel Aviv University RoboBoat team, SAIL-IL.**

I. Introduction

SAIL-IL is the Tel Aviv University's Engineering Department RoboBoat team, founded in July of 2020 it is the first team to compete in the RoboBoat competition from the state of Israel. The team was founded by fourth year engineering students with the mission of creating a sustainable RoboBoat program that would allow students to deal with and solve real world problems.

The inherent challenges of starting a new program and designing a competitive ASV led us to utilize a fail fast approach to development. With future teams in mind, we emphasized building institutional knowledge and documenting our mistakes and decision-making process.

II. Competition Strategy

Since it is our first year, we needed to design and develop the ASV from scratch. We quickly realized the challenges of developing an ASV during lockdowns and other COVID-19 related limitations. For long durations during lockdowns, we did not have access to our lab or field testing.

This led us to a strategy that would maximize points while maintaining lower development risks. We adopted a strategy of attempting high value tasks that require similar system capabilities, such as the navigation channel, obstacle channel, obstacle field and speed gate. All these tasks are based on recognizing and classifying buoys and have similar navigation and maneuverability requirements, and most of the development for these capabilities could be done in parallel. This also allowed for development redundancy, for example obstacle avoidance using Computer Vision and LIDAR in case one was not sufficient.

during our research phase we compiled a database of design decisions made by past teams. Using past programs TDR's and long conversations with very helpful competitors that shared their knowledge in a wonderful show of sportsmanship, we could analyze different strategies and design features to find patterns. Under the assumptions that bad decisions where less likely to be repeated we could avoid common pitfalls, for example we quickly concluded that the BlueRobotics thrusters were common thanks to their reliability and ease of use.

In line with our high value tasks strategy, we decided to attempt the object delivery task using a kit drone, this would allow us to continue the mission while the drone was delivering objects, it did not require major changes to the ASV design, and it allowed for parallel development with limited resources as we have only one fully equipped hull.

We based the entire software architecture on ROS [1] as a development strategy. To lower risks during integration, we required all off-the-shelf components integrated in our system to have built in compatibility with ROS. This decision saved us from writing labor intensive drivers or SDK's. In addition, we connected the ASV, UAV and base station through a distributed ROS network, thus eliminating the need to write Server-Client infrastructure from scratch.

at the beginning of the design process each task received a priority grade, the higher the grade the greater the resources we were willing to invest in tackling the task. This made dropping unreachable goals early on easier, which in turn meant we did not waste time on them. Since this is our first year competing, we raised funds for the project throughout the year. Prioritizing tasks allowed us to reach development milestones even before we had the necessary funding. Furthermore, we performed a cost benefit analysis on each design component to best utilize our limited budget. For example, the decision to use a GPS-RTK system as opposed to an GNSS aided INS (like the VectorNav VN-300 utilized by other teams) was aided by the cost analysis. We realized that similar performance could be achieved since the ASV is always in range of the base station and relatively slow moving.

The following subsections are in the order of task priority. Early in the design process we decided not to attempt the acoustic docking task as it would require a niche subsystem that did not fit our strategy.

A. *Navigation Channel*

To demonstrate basic autonomous capabilities, the navigation task is mandatory and must be completed first, before any other tasks can be attempted. The ASV needs to reach a GPS start location that is given in advance, and pass through the two gates 6-10 ft wide. The navigation channel task is a development milestone, in order to achieve the capabilities needed to complete the task we implemented a method of continues integration and testing. After the end of the third COVID-19 lockdown we tested new integrated features each week on the water, this meant we could identify and debug problems quickly.

B. *Obstacle Channel*

The obstacle channel requires the ASV to identify the next gate and update the current path so that it passes through said gate. In contrast with the navigation channel, the path through the obstacle channel would not be linear and the greatest risk would be to hit a buoy. We decided to prioritize maneuverability and platform stability over speed, this led to the catamaran design with azimuth stern thrusters described in the Design Creativity section.

C. *Obstacle Field*

The purpose of this task is to test the ASV complex path planning and maneuverability. The ASV needs to track the pill buoy ant the center of obstacle field and locate a path between the obstacles to reach the pill buoy, circumnavigate it and exit the obstacle field. In order to always keep visual contact with the pill buoy and track the obstacles surrounding the ASV, the ASV is equipped with two ZED2 stereo vision cameras set 60° off center, each camera has a FOV of 120° so together the vision system has an FOV of 240°. The full obstacle acquisition and mapping system is described in the design creativity section.

D. *Object Delivery*

we decided to use a UAV as the object delivery system as it would allow the ASV to continue its mission simultaneously to the UAV. Since we only had funding and time to build one fully equipped ASV the sub teams needed to coordinate work on a limited resource. Using the UAV ment we could develop its capabilities in parallel to the ASV development until the integration stage.

To promise easier integration with the ASV and base station we decided to use a drone that could connect to the ROS network over Wi-Fi. We could not find a commercial, ready-to-fly drone within the required specifications, so we built a kit drone and added an onboard Jetson Nano that could control the autopilot and communicate with the ROS network.

an object delivery system is mounted on the undercarriage of the drone frame. The objects are placed at the start of the run in the delivery system. when the UAV is in position above the target a continues servo will rotate the mechanism and allow the object to drop (figure 1)

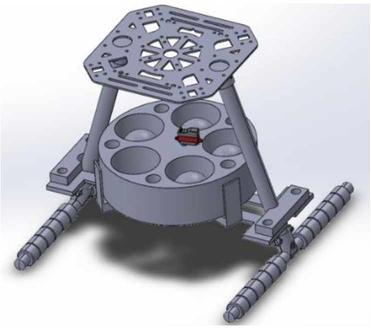

Figure 1 - UAV object delivery assembly

Due to new, and not well documented, regulations in Israel for drones and radio systems, acquiring the drone kit took several months. This unfortunately meant we could not complete the UAV development in time and as of submitting this report the drone can only fly a pre-determined path.

III. Design Creativity

A. *Propultion Design*

As stated in the Competition Strategy section We decided to prioritize maneuverability and platform stability over speed, this led to the catamaran design with azimuth stern thrusters as opposed to a faster monohull. The catamarans greater beam and counter-acting hulls would decrease roll especially during tight maneuvers where we are likely to cross our own wake. The vectored thrust of the azimuth thrusters would allow the ASV to follow a curved path with minimal changes in velocity, minimizing pitch rocking. In order to keep clear of obstacles at low speeds the ASV is equipped with bow thrusters embedded into the hull, when the stern thrusters are at 90 ° it would allow for “crab like” movements (figure 2). Unfortunately, because of time constraints we were not able to implement the control system for the bow thrusters.

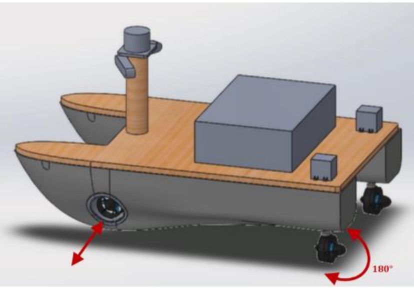

Figure 2 - stern azimuth thrusters and bow thrusters

designing a thruster axis assembly that could rotate the thrusters 180°, pass through the hull and stay watertight was a technical challenge. The hull itself is made of foam covered in fiberglass, any water in the axel shaft (figure 3) would soak the foam and compromise the hulls buoyancy over time. We designed and milled a costume axle rod and sealed it using a V-ring house in a milled nylon housing.

Image 1- Gallili final design

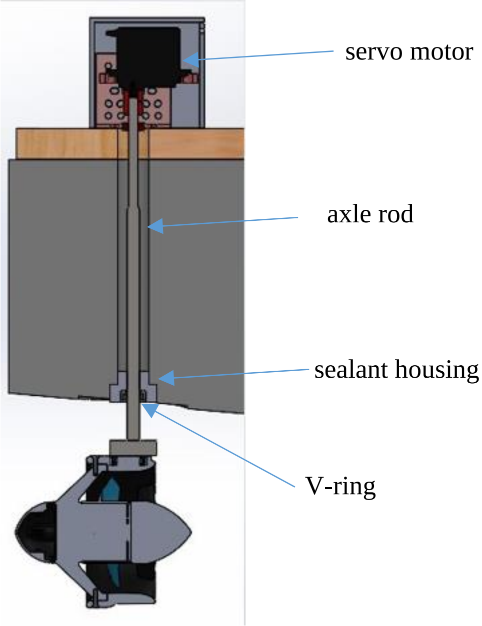

Figure 3 - azimuth thruster assembly

B. *Obsticle Detection*

We used datasets from previous competitions and veteran teams that were manually tagged and used to train a YOLOV4 model [2] that could detect and classify buoys by type and color using the darknet framework [3] . (figure 4)

The identified buoys bounding boxes were passed to the obstacle mapper, for each bounding box the mapper would calculate the position of the buoys center relative to the ASV center line using a point cloud of the environment (figure 4), this is less computationally expensive than mapping the entire 3D environment with a particle-filter based SLAM algorithm.

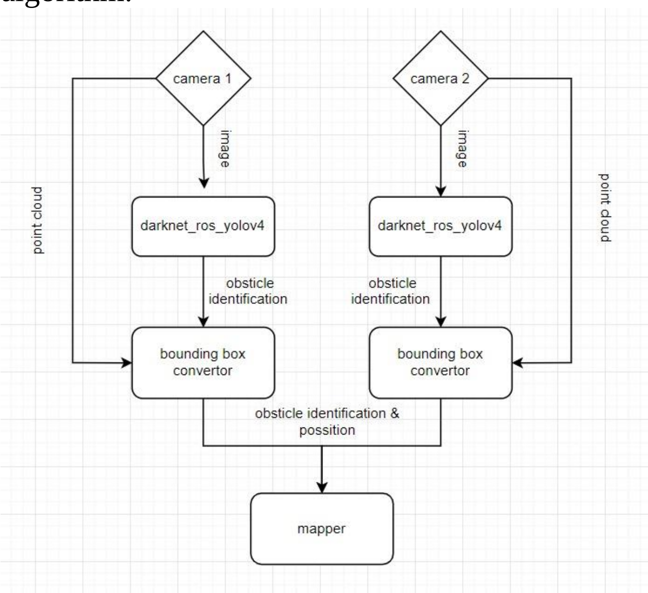

Figure 4 - obstacle detection system overview

1. *Training the Network*
   Like any neural network, a high quality dataset is essential, the challenge was to acquire such a dataset as a new team. Using datasets from previous competitions as well as one generously provided by the another team we manually classified and then trained the YOLOV4 model without ever seeing a real buoy.
   To make our model more robust and generalized, we used data augmentation techniques on our dataset to generate more diverse samples. All samples in the dataset were tagged rigorously to insure the datasets quality (figure 5).
   During the covid lockdowns we could not benchmark the NN using real buoys on the lake. Instead, we set up our ZED2 camera in front of a television screen and played a recording of the course from a previous year (figure 6). Our NN was able to recognize buoys with over 80% accuracy.

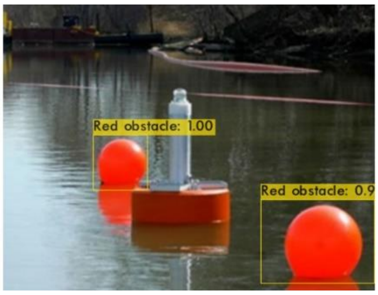

Figure 5 - training data scraped from google images for greater robustness

2. *Detection Optimization*
   We used the Nvidia Jetson Xavier NX board with an integrated GPU as our onboard computer. there were several factors in the decision to use the Jetson NX board, the first was a large online support community working on similar CV problems. Secondly, we received several boards from our sponsors, freeing crucial funds for other components. Initially we were only able to achieve low framerates of 2-5 fps that would overwhelm the CPU. We were able to substantially optimize the NN by converting our trained model to a YOLOv4 tiny 3L [4] model that decreased accuracy slightly but increase framerates to 30 fps.
   We utilized the network features of ROS to distribute our on-board processing over three boards thus freeing up computing power and memory for other tasks. This allowed us to run two parallel stereo cameras each on a dedicated GPU, as well as LIDAR and localization and navigation software without losing performance.

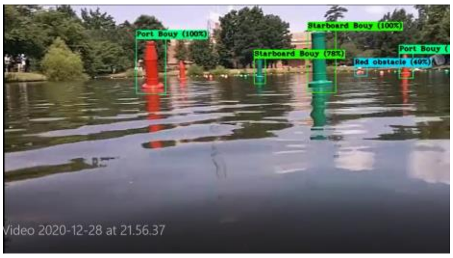

Figure 6 - benchmarking NN with video from previous years

3. *Obstacle Mapping*
   Many algorithms that attempt to solve the SLAM problem are based on map features in order to update the robot's location. This was our initial approach, but after some testing with our sensors (LIDAR and stereo vision camera) we noticed that the environment was sparse at times. This ment that localizing based on the changes in the map would be difficult and inaccurate. For that reason, we decided to localize our position separately to the mapping function.

   In our initial design we planned to detect and classify obstacles using computer vision and mapping them using the LIDAR point cloud. We created an algorithm to map recognized obstacles. For each obstacle recognized the algorithm would locate the detected bounding box in the point cloud, then calculate the center position of the obstacle relative to the ASV from the corresponding subset. This algorithm was designed to be used with the LIDAR but because of shipping delays we implemented it using the ZED2 stereo vision cameras as part of our redundancy plan.

Next year we plan to implement the mapping algorithm using stereo vision for short range and LIDAR for long range.

C. *Path Planning and Control*

During our research phase we discussed the main challenges for a new team with veteran teams. We learned that creating a controller for the vessel that could follow a curved path would be very complicated for inexperienced control engineers.

As part of our development risk reduction strategy, we decided to use an open source Pixhawk controller because of its capabilities and compatibility with ROS. To the best of our knowledge no one has created a Pixhawk controlled vessel that is integrated with an onboard computer running ROS. We initial planned to calculate a local path using the TEB (Time Elastic Band) method [5], a cost map based local planner that is optimized for sparse maps. The path would then be passed into the Pixhawk controller as a trajectory to be followed (figure 7.a).

While the TEB planner worked well in simulation, during the final integration stage we discovered the Pixhawk controller could not receive such a dense trajectory. At this stage, the reliance on the flexible Pixhawk was a clear advantage, we could quickly change our software architecture to pass a queue of waypoints calculated by the path planner to the controller instead of passing the required trajectory (figure 7.b).

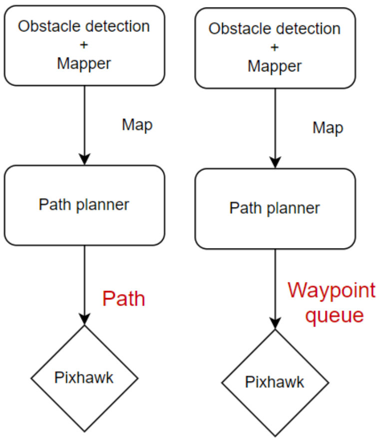

Figure 7.a path *Figure 7.b waypoint queue*

The Pixhawk was a low-cost option with useful built-in features that we could integrate quickly and reliably.

1. The built-in ability to switch between remote controlled and autonomous mode as required in the competition rules.
2. We used the open-source ground control station Mission Planner to calibrate the PID controller iteratively and remotely in a few hours (figure 8), this saved us the need for a complex physical model and the results where within our desired parameters.

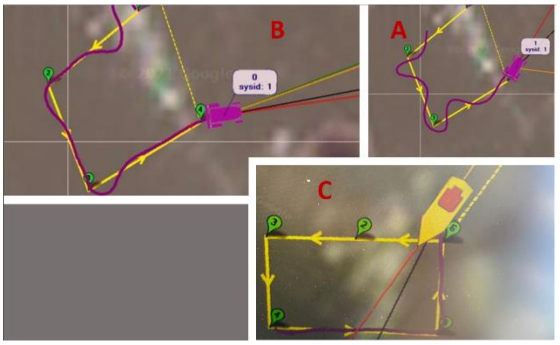

Figure 8 - calibrating turn rate PID with Mission Planner

IV. EXPERIMENTAL RESULTS

A. *Development Methodology*

As this is our first year competing in the RoboBoat competition we designed and developed the ASV from scratch. We defined the following development stages (figure 9) with continues integration and testing in mind, each team had specific features to develop at each stage and integrate into the prototype until the end of the stage. A continuous integration approach meant we tested separate features on the water each week during the stage. Each stage culminated in an all systems test to ensure design flaws and system failures would be detected as soon as possible.

Floating platform – design and build the first hull mockup without a propulsion system or sensors. The purpose of this stage was to test the hull dynamics as well as to allow parallel development of other sub-systems on an existing mockup as quickly as possible.

Controlled – integrate the propulsion and power systems and remote control the vessel.
Obstacle avoiding – the vessel can sail to a predefined waypoint and can detect and avoid an obstacle in its path.
Situational awareness and path planning – the ASV can map obstacles at a radius of 24ft and plan path to the next global waypoint.
Full autonomy – implement the full state machine that will switch the ASV modes between missions and handle a complete course run.

As a result of COVID-19 restrictions we decided to merge the floating platform stage with the controlled stage, and since the first prototype excided our maneuverability requirements, we continued with our initial hull design.

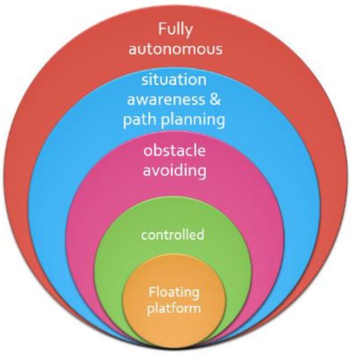

Figure 9 - development and testing stages

B. *Platform and Remote Control Tests*

Due to COVID-19 our first test sailing the bare prototype in water was on the 7th of January 2021, we tested the vessels maneuverability, controller range and waterproofing (figure 10).

Figure 10 - remote control test

C. *PID Callibration*

using the open source and versatile Pixhawk controller meant we could calibrate the PID controller within a few hours using the compatible ground control station GUI (figure 8). After calibrating the PID we tested the ASV's ability to follow a dense path of waypoints. The results excided specifications (figure 11)

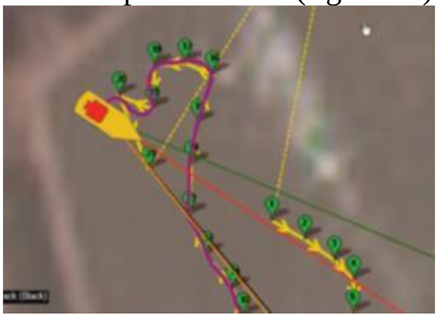

Figure 11 - path with dense waypoints

D. *Object Detection and Mapping*

after testing the neural network's ability to detect and classify buoys, we tested the obstacle mapping algorithm in different environments, the buoy is classified by the NN, the bounding box of the object is the passed to the mapping algorithm which calculates the relative position of the buoy and sends it to the path planner (figure 12)

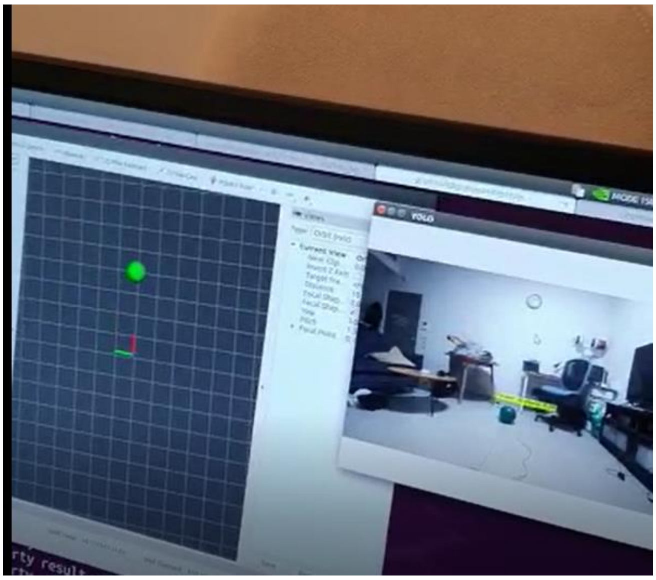

Figure 12 - testing object mapping algorithm

E. *Testing the LIDAR*

the initial ASV design included a 16-channel 3D LIDAR (Velodyne VLP-16) but due to lack of funding, we could not purchase the component. Relatively late in the development process we received a Quanergy M8, 8-channel 3D LIDAR on loan from one of our sponsors. After testing the LIDAR's capabilities on the smallest buoys, we discovered our initial assumptions were incorrect. The beam density of the LIDAR at 30ft was too low to properly capture the buoys and the point cloud at that range was very noisy (figure 13). This meant we could not use the LIDAR to estimate the location of buoys identified by the vision sensors as planned and we decided to map the obstacles using only the stereo vision cameras.

Initially we planned to mount the LIDAR on a gimble to insure it was parallel to the ground plane, but after reviewing the testing data (figure 13) we understood that the changing pitch of the sensor could be an advantage. Next year we plan to create a filter that could sample the lidar signal over time and detect the shadows created by the buoys (figure 13). This could allow us to detect obstacles at a much greater distance.

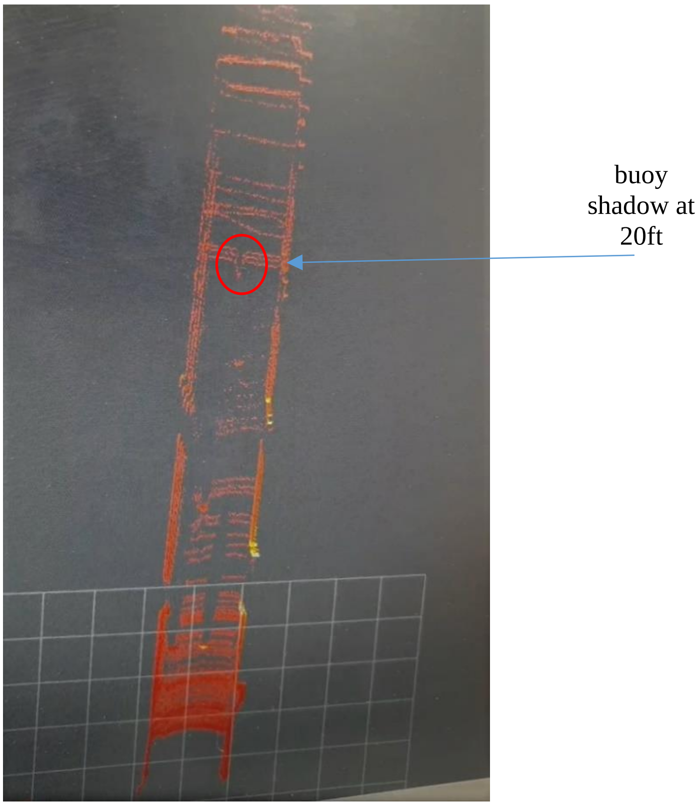

Figure 13 - testing 8-channel LIDAR with buoys

F. *SITL and ROS*

Serial communication between the onboard computers and the Pixhawk controller was implemented using the MAVROS [6] ROS package. The integrations are complex and time consuming so running the SITL (software in the loop) simulator to simulate the Pixhawk behavior (figure 14) saved hours of on the water debugging and was another advantage of using the Pixhawk running the ArduRover firmware.

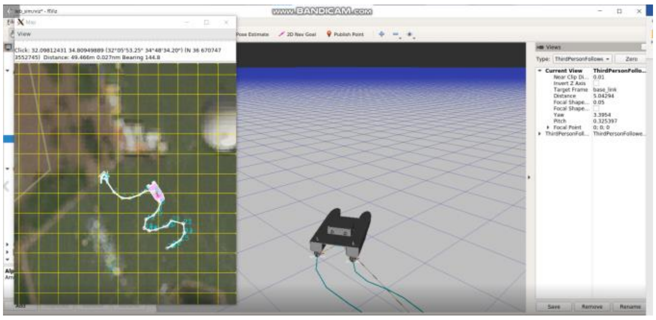

Figure 14 - SITL and ROS simulation

V. ACKNOWLEDGMENTS

Looking back on everything we have achieved during the past year and taking into account COVID-19 and a two-week war it is a massive task. Even without one of our wonderful supporters and mentors the project could not succeed, and we would like to acknowledge them.

Jacob Fainguelernt and Danny Berko are the programs academic directors and Tel Aviv University faculty members. They have believed in the team from the beginning and have fought tooth and nail to see us succeed.

Hanan Spond is an experienced systems engineer and project manager. He was the systems engineering and team management mentor and his sage advice and calm demeanor pulled us through many crises.

Each of the seven sub teams had a mentor, each an expert in their field, full of knowledge and experience to share. Bental Tavor, Amitai Peleg, Amir Kirsh, Hanoch Aharon and Danny Berko.

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- Tzvika Webb from Synopsis
- Nvidia
- Adar Adler form Xenom
- Moran Nir from Amazon

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VI. REFERENCES

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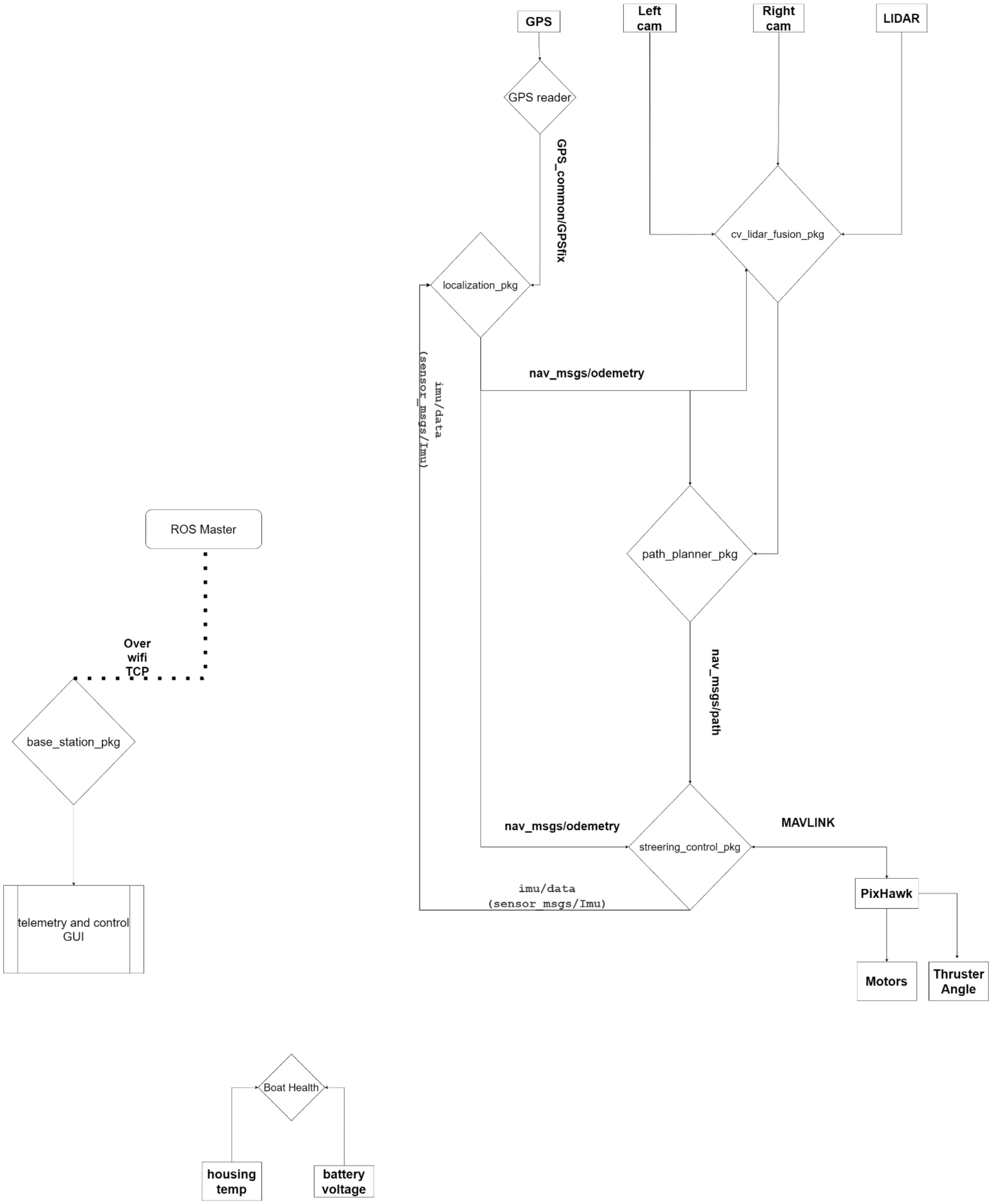
VII. APPENDIX A: COMPONENT SPECIFICATIONS

component	vendor	model/type	specs	cost ($)
ASV Hull form/platform	xenom	custom made	fiberglass covered foam hulls with plywood deck	
Waterproof connectors	Local building material supplier	IP65 outdoor junction boxes		
Propulsion	Bluerobotics	T200	T-200 specs	161
Power system	Fullymax	Lipo 14.8V 5.0Ah	-	129
Power system	Fullymax	Lipo 7.4V 7.5Ah		123
Motor controls	Pixhawk	Pixhawk 2.4.8	Pixhawk 2.4.8 specs	
CPU	Nvidia	Jetson Xavier NX	Jetson xevier-nx specs	
CPU	Nvidia	Jetson Nano	Jetson nano specs	
teleopration	Radiolink	AT9s + RD9s	AT9s specs	353
teleopration	Ubiquti	Bullet M5	Bullet m5 specs	
compass/GPS	Ublox	c94-m8p	C94-m8p product summary	463
compass/GPS	DFRobot	SEM0140 10 DOF MEMS IMU sensor	SEN0140 specs	46
Inertial Measurement Unit (IMU)	StereoLabs	zed2 - internal IMU	Zed2 specs	500
Camera(s)	Quanergy	M8	100m range, 360° FOV, 24 VDC,	
LIDAR	StereoLabs	zed2	Zed2 specs	500
Aerial vehicle platform	Holybro	X500 kit	X500 kit description	470
Motor and propellers	Holybro	X500 kit	X500 kit description	
Power system	Fullymax	Lipo 14.8V 5.0Ah	-	129
Motor controls	Pixhawk	Pixhawk 4	Pixhawk 4 specs	
CPU	Nvidia	jetson nano	Jetson nano specs	
Camera(s)	Pitel	5MP 1080p camera module	1080p @ 30 fps, 720p @ 60 fps and	21

			640*480p 60/90 video recording	
Autopilot	Ardupilot	Ardurover boat		open source
Algorithms		TEB local planer		
Vision		YOLOv4 and darknet		
Localization and mapping	custom			
Autonomy	custom			
Team Size (number of people)	15			
Expertise ratio (hardware vs. software)	2:3			
Testing time: simulation	100+			
Testing time: in-water	80+			
Inter-vehicle communication	ROS-network over 5GHz Wi-Fi			
Programming Language(s)	Python, ROS, C++			

VIII. APPENDIX B: SYSTEM ARCHITECTURE



IX. ELECTRICAL DIAGRAM