DESIGN AND DEVELOPMENT OF AN AUTONOMOUS UNDERWATER VEHICLE - LAPRAS

Mihir Ranjan, Megha Goyal, Dhruv, Harshul Bansal, Siddhant Verma, Gunagya Singh Mamak, Sriram Chava, Saurav Ranjan, Shivang Dudani, Utkarsh Verma, Shorya Kumar, Kritika Bansal, Rajat, Sundeep Chand, S. Suchit, Chirag Garg, Samarth Sachdeva, Suryansh Gangwar, Ishpreet Singh Luthra, Utkarsh Kuchhal, Shivam Rastogi, Saransh Goel, Md Masood Raza, Abhinav Aggrawal, Rakshit Garg

Delhi Technological University, Shahbad Daulatpur, New Delhi-110042, India

ABSTRACT:
LAPRAS is the flagship Autonomous Underwater Vehicle developed at Delhi Technological University. As first-time participants at RoboSub, the vehicle was designed to be compact and robust while simultaneously being able to function as a reliable AUV to complete all required tasks and unmanned operations. This entailed a massive design overhaul with improving vision processing and a comprehensive round of simulations and testing the final design that exhibited a clear improvement compared to our previously created designs.

I. COMPETITION STRATEGY

To coordinate well in a remote work environment, we had to introduce some significant changes in the software department workflow. Using a monorepo on Github to hold all the project files helped us collaborate seamlessly in a remote working environment. This enabled us to start testing our vision and control algorithms early on.

For enhancing the colours in the videos captured, we decided to use our image dehazing method[1], on which we started working recently.

Coming to our task strategy, we decided to pick the G-Man side since detecting the corresponding props would be easier from the vision perspective as they are quite distinguishable. The smaller torpedo opening of the bootlegger is a trapezium that is easier to aim for than a star. For the buoy task, we would need a rough estimate of the distance to the buoys, which could be done using a simple vision algorithm since the buoy dimensions are known, as once the bot gets close to them, detection would not work. For the torpedo task, to reduce the chances of failure, we decided to first shoot through the bigger opening and then through the smaller opening. In the bin task, our strategy is to use two markers. Once the first marker is dropped, we would track it and based on its success, we would take the second attempt if needed.

Once the bot reaches the centre of the octagon through the pinger guidance, we start searching for the bottles located on the table via object detection through the front & the bottom camera. Once the position of the bottle is localised we pick it up and resurface at the centre of the octagon. Then we try to find the table having dollar sign, by searching for it, along the diameter of the octagon and finally we try to place the bottle on the table after localising it. Then we try to repeat the previous steps, by moving to the centre of the octagon, till no bottle is left on the platform.

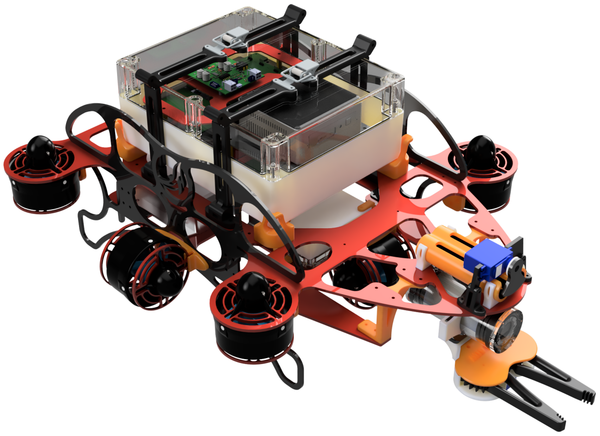


Figure 1.1 - Cad render of Lapras

II. DESIGN RATIONALE

A. MECHANICAL DEPARTMENT

FRAME

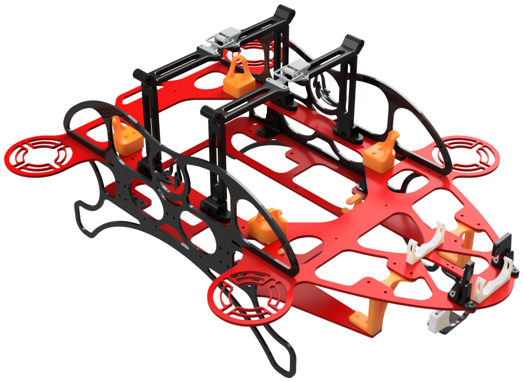


Figure 2.1 - Frame Render of Lapras

The frame of Lapras is the main supporting structure in the assembly. The structure is well optimised to avoid stress concentration and to sustain the loads without any considerable deformation or failure. The frame is designed to have minimum assembly time, easy access to the components attached and structural strength under static and dynamic conditions.

The sheet metal parts of the frame are manufactured using waterjet cutting technology. It makes precise cuts to the metal necessary to manufacture the frame's intricate cavities and edges. The frame is made up of aluminium 6061-T6 alloy, selected considering the harsh working environment and operating conditions. The bottom plate is attached to the base plate using 2mm stainless steel L-brackets, manufactured using sheet metal bending operation. The mounts and fixtures for the hulls are produced by FDM based 3D printing of ABS material, chosen as it absorbs and dampens the structural vibrations to acquire precise dimensions and strength of the design. The base plate holds the main hull, front camera hull, 4 heave thrusters, 2 sway thrusters, 4 heave thrusters, torpedo launcher and gripper. Each side plate holds one surge thruster each. The bottom plate holds the battery hull, bottom camera hull and dropper.

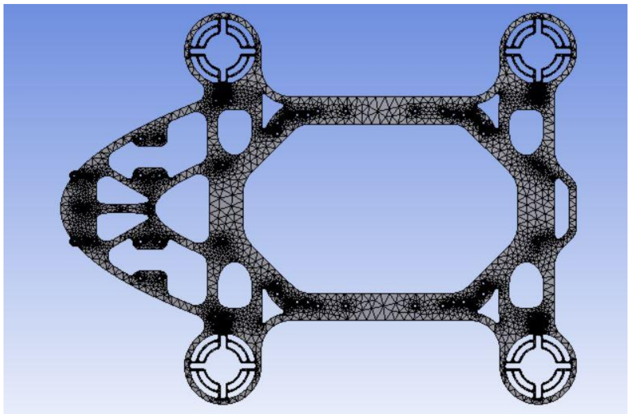


Figure 2.2 - Mesh of Lapras base plate

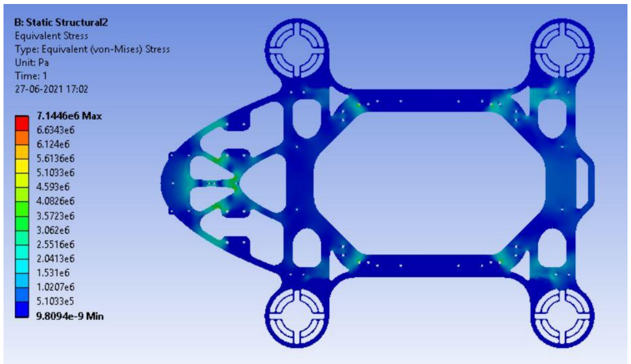


Figure 2.3 - Stress analysis of Lapras base plate

The structure is smartly designed so that the base plate not only act as the mounting space for the electronic housing and manipulators but also it has shrouds for the heave thrusters, thus the placement of the base plate was crucial as we planned to place heave thrusters in the plane of centre of gravity for higher propulsion efficiency.

CUBOIDAL HULLS

The AUV has 4 hulls in total attached to its frame. Except for the front camera hull, all the hulls are cuboidal in shape. It is easier to store, access and monitor electronic components in a cuboidal hull as compared to cylindrical hulls, where it was not possible to utilise the complete volume in a clean way.

The main hull is mounted upon the frame with the help of 4 wall mounts and 2 latches, here the latches secure the hull in place.

The battery hull is made up of aluminium to dissipate the heat generated by the buck converters. Thus eliminating the need for a dedicated cooling system.

THRUSTER PLACEMENT

AUV has a total of 8 T200 thrusters, which are placed as follows:

- 4 heave thrusters are placed at the base plate that controls the roll and pitch of the AUV.
- 2 sway thrusters are placed at the bottom plate to control yaw.
- 2 surge thrusters are placed at the side plates.

Overall the AUV has 6 degrees of freedom.

MANIPULATORS

1. TORPEDO LAUNCHER

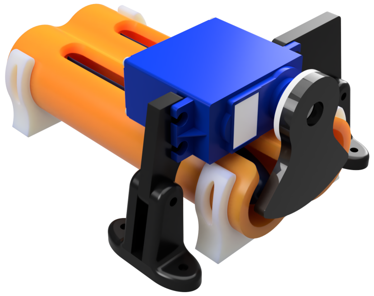


Figure 2.4 - Design render of Torpedo Launcher

The torpedo launcher system consists of two parallel launch tubes, 3-D printed with springs mounted at their ends. The launch tubes are placed adjacent to each other to reduce the inaccuracy of the torpedo. The tubes are attached to the frame with the help of 2 snap-fit attachments, this makes it easy to load the torpedoes. The torpedoes are kept inside the launch tubes with the help of a circular cross-section (obstruction plate) made up of aluminium (6061-T6 alloy). The obstruction plate is controlled by a waterproof servo motor, mounted above the launch tubes with the help of latches for easy assembly. The servo motor rotates by an angle of 30 degrees from the mean position for a successful launch.

The front of the torpedo is ellipsoidal. This reduces the stress at the tip and thus protects from deformations. The tapered cylindrical body of the torpedo is ideal for reducing drag and mass simultaneously. The torpedo has 4 fins that prevent any unwanted deviation from its trajectory.

The torpedo has a slenderness ratio of 14.66

Torpedo Coefficient of Drag:

Drag Force = $\frac{Cd*A*\rho*V^2}{2}$

Vertical deviation = $\frac{Net\ Thrust*T^2}{2}$

$$T = \int_{0}^{0.3} \frac{dx}{V}$$

Where, $V^{2} = Vl^{2} - \frac{Cd*A*\rho*V^{2}*x}{m}$

$$T = \int_{0}^{0.3} \frac{(1 + \frac{Cd*A*\rho*x}{m})dx}{Vl^{2}}$$

Where,

C_d = Coefficient of Drag

A = cross-sectional area of Torpedo

ρ = Density of Water

V = instantaneous velocity of torpedo

V_L = launch velocity of torpedo

m = mass of torpedo

T = total time travelled

Simulating the torpedo for speeds ranging between 0.25 m/s to 2m/s :

C_d = 0.091

Taking maximum vertical deviation to be 0.5 cm, the launch velocity comes out to be 0.46 m/s. The escape velocity of the torpedo is around 0.46 m/s in water, this speed is sufficient for the torpedo to hit the target from a safe distance without any deviation and without damaging anything in the environment.

2. DROPPER

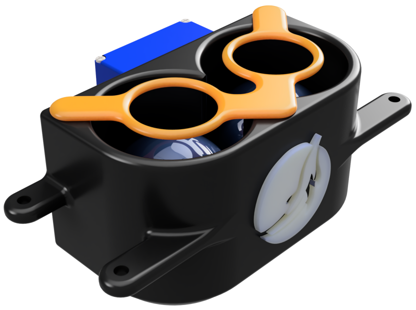


Figure 2.5 Design Render of Dropper

The dropper for the AUV holds two solid steel balls (Markers) adjacent to each other, separated by a partition. The markers are dropped by rotating a heart-shaped plate placed perpendicular to the dropper. The balls then free fall under the influence of gravity. The dropper body is kept adjacent to the bottom camera for better mapping and accurate dropping. The obstruction plate has a circular cut in the centre, which is designed to lower the total rotation made by the servo motor, which significantly reduces any chance of failure. The servo motor has to rotate 30 degrees from the mean position to release the marker. The markers are placed in their respective cylindrical cavities, and a detachable cover is used to secure them from the top. The dropper body is made up of ABS plastic and is manufactured by the 3-D printing process. This design is adopted as it takes up a small amount of space and requires only one waterproof servo motor to operate.

3. GRIPPER

Figure 2.6 Design Render of Gripper

For most of the manipulator designs we focussed on workability and simplicity, thus the gripper for Lapras is manufactured by 3-D printing, and the material used is ABS plastic considering its high strength to weight ratio. The gripper fingers have toothed gears in contact with each other and are constrained to rotate together. A servo motor is mounted above the fingers, which provides torque to the whole system. The shape of the fingers is triangular, with the internal surface slightly curved inwards for easier gripping of circular and cylindrical objects. At the end of each finger, abrasions are made to increase the gripping strength and make lifting the bin covers easier in the marker dropping challenge. A cavity is made in each finger, which sheds off excess mass while retaining structural rigidity and strength.

B. ELECTRONICS DEPARTMENT

The main hull houses all the electronic components, and the lithium polymer batteries have been placed in a separate hull. Multiple PCBs have been designed to reduce the wiring and make the connections more modular. Individual PCBs have been designed for Power distribution, Sensor and motor control and for cutting off and switching the batteries.

1. Power

The Power Distribution Board (PDB) was custom designed and had a buck converter for the servo motors. The PDB enables us to power all the electronics onboard. PDB distributes power to the thrusters, servo motors, Intel NUC through the DC-DC NUC, which boosts 12V to 19V and the hydrophones. The Intel NUC powers the microprocessor board. The buck converter drops the 12VDC to 7VDC for the servo motors. A buck converter is also implemented for 12VDC - 5VDC for the acoustic systems. A DPDT switch located outside the AUV is connected between the DC-DC NUC and the PDB as a kill switch to halt the vehicle’s functioning.

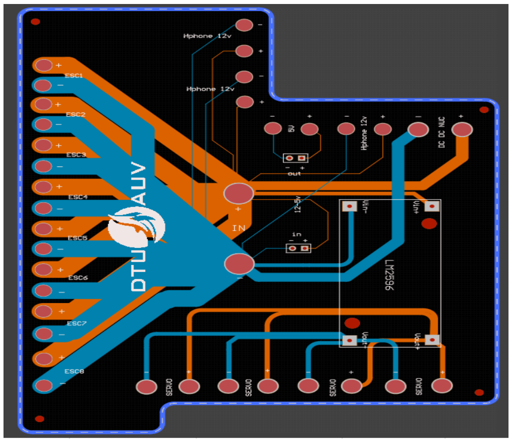


Figure 2.7 Power distribution board

S.no	Component	Current draw
1	Thruster (T200)	4A
2	Servo Motor (HS5646WP)	2.1A
3	Intel NUC (NUC7i7BNH)	3.5A
4	Arduino Mega	0.6A
5	Hydrophone (Teledyne TC4014)	0.028A
6	MAX11043ATL	0.5926A

Total current being drawn at all times =
6 x (4A) + 1 x (2.1A) + (3.5A) + (0.6A) + 3 x (0.028A) + 0.5926A = **30.8766A**

Total battery capacity = 10000 + 10000 mAH = **20000mAH**

Ideal operating time of Lapras =
20000/30876.6 = 0.6477 hours **= 38.86 minutes**

The servo motors will not be working simultaneously, only one servo will operate at a time. Similarly a maximum of 6 thrusters will be operating at once. The runtime has been calculated by taking these situations into consideration.

2. Battery monitoring system

2, 4 cell Lithium polymer batteries with a total capacity of 20000mAH were chosen for the input power. A custom battery monitoring system PCB was designed, which continuously monitors the cell voltage and the total voltage of each battery and cuts it off from the circuit as soon as it reaches the threshold minimum voltage (3.1V). This circuit also switches between the two batteries through the inrush as soon as one is cut off. Previously, a market purchased battery management system was used, But after thorough testing and designing, this PCB was finally used.

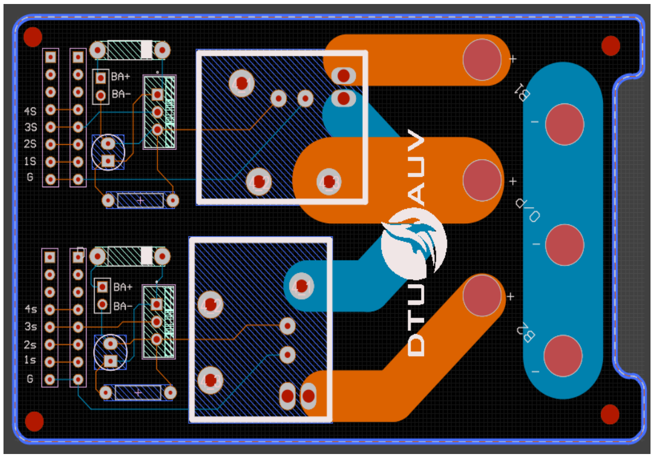


Figure 2.8 Battery cutoff/switching circuit

3. Higher-level control board

A microprocessor board for sensor and motor control was designed by the team. Arduino Mega 2560 was chosen as the microprocessor for higher-level control because of the high number of PWM, digital, and analog pinouts. This PCB acts as a shield for the Arduino mega; It has pinouts for the IMU, Pressure sensor, current sensor, servo motors and ESCs. The processed sensor data from the Arduino mega is relayed to the CPU using the Rosserial protocol. Current sensor ACS712 has been implemented to monitor the current drawn by the gripper servo motor. By monitoring this current it can be determined whether the gripper has successfully grabbed the object or not. All the grippers implemented in our previous ROVs and AUVs did not involve this technique. Using this significantly increases the success rate of the gripper involved tasks.

Apart from the current sensors, Voltage sensors and temperature sensors can also be attached to this PCB which find their use during the debugging phase. It was noticed in the previous vehicles that wiring increased debugging periods—developing the microprocessor PCB greatly improved this situation.

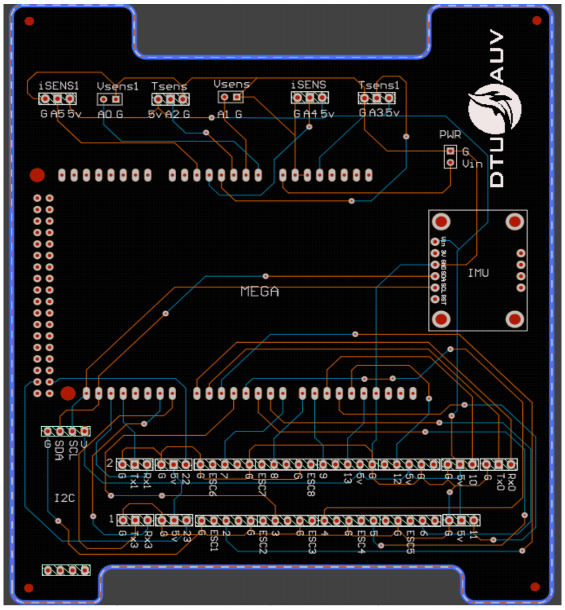


Figure 2.9 Microprocessor board

4. Acoustics

We have used three Teledyne Reson TC4013 hydrophones placed in a right isosceles triangle with a side length of 27.2 cm. The acoustic stack consists of two boards, namely the data acquisition board and the digital signal processor. We have used Maxim's MAX11043ATL Evaluation Kit, which along with the simultaneous sampling of ADCs, has an integrated programmable amplifier, anti-aliasing filter, and digital filters. The data acquisition board's data is sent to the digital signal processor via the SPI communication protocol. We have used the Texas Instruments LAUNCHXL-F28379D microcontroller as our DSP to lay off the strain from our main CPU. The coordinates of the pinger are calculated by TDOA and sent to the Intel NUC via USB.

The hydrophones have been carefully placed away from the thrusters to reduce the effect of noise in the input signal captured by the hydrophones. The placement was done keeping in mind the dimensions of the hydrophones and symmetry. The arrangement has been kept such as to maximise the value of receiving time difference which makes the algorithm easier to compute and estimate values.

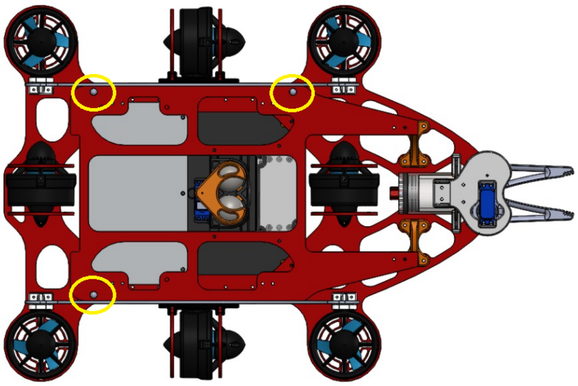


Figure 2.10 Hydrophone placement

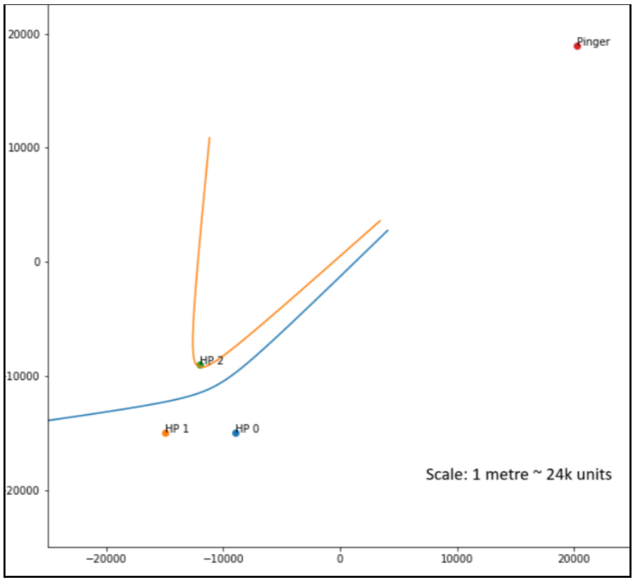


Figure 2.11 Hypothetical arrangement

We have used an approximate model of 2D TDOA localisation, using 3 hydrophones neglecting the Z-plane delay, which gives us substantially reduced complexity in exchange for some loss in accuracy. In order to compensate for the lost accuracy, we will be using the camera modules considering the fact that the pinger tasks include the presence of visually distinguishable objects present which will be easier to detect using cameras.

The algorithm computes the time difference of arrival of multiple nodes wrt 1 node to form a hyperbolic line of positioning to find the unique solution of the pinger. This estimation is done recursively for the auv to move in the direction of the calculated location.

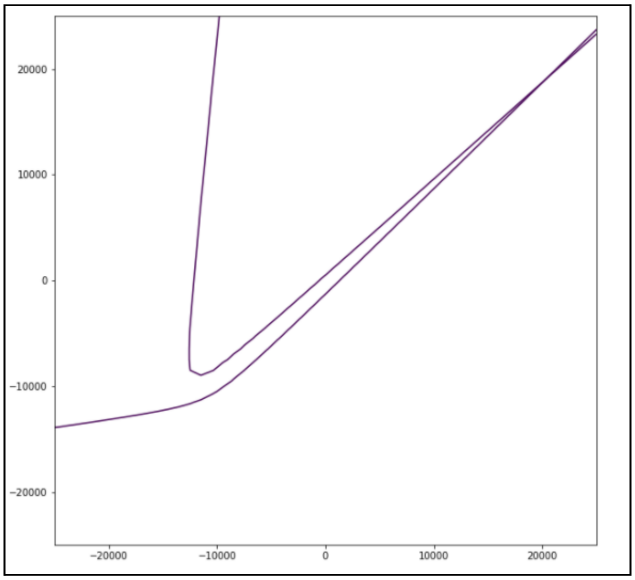


Figure 2.12 Estimating pinger

C. SOFTWARE DEPARTMENT

1. Underwater Image Enhancement

Recently we started working on underwater image colour enhancement techniques to improve the image quality for the object detection algorithms. We implemented an algorithm based on the Underwater Single Image Dehazing [1] method. To check the performance of the method used, we used the video data from the 2018 tasks.

Figure 2.13 Result of image enhancement on path marker

2. Detecting the Targets

We would use YOLO v3 real-time object detection, along with colour thresholding (for segmenting parts from images) and contour detection (to detect borders of objects and localize them) for detecting the objects. We calculated the center of the bounding rectangle around the object for alignment. When rotationally aligned with the target, we used the property, the bounding rectangle will be a perfect rectangle instead of a trapezium to control the AUV. However, to implement the vision algorithms in Gazebo, we used OpenCV based object detection techniques. These techniques sufficed to test the vehicle's overall control; however, in a real-world scenario, using the YOLO object detector would help us improve our accuracy to a great extent.

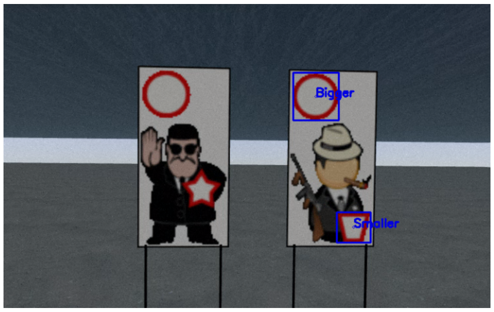


Figure 2.14 Identifying and classifying the targets in torpedo task

3. Distance Estimation

In order to accomplish certain tasks, like the buoy task, it was necessary to determine the distance between the camera and the target. So to do this, the concept of "Triangle Similarity" was used. The performance of the algorithm was tested inside Gazebo, and it gave us fairly good estimates of the distance to the target.

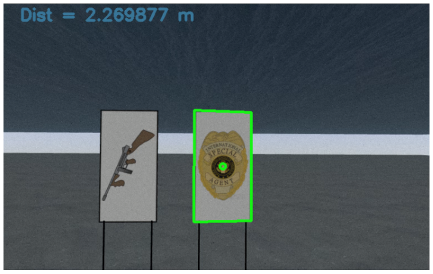


Figure 2.15 Estimating the distance to the target.

4. Simulations

We used Gazebo simulator along with the UUV package to simulate our AUV in the underwater environment. Gazebo provides plugins for various sensors like camera, IMU, Pressure sensor, etc. using which we were able to mimic the bot's sensors. Having a simulation environment setup in Gazebo helped us to test our controls and gain enough confidence in our algorithms that they will perform well in the competition environment.

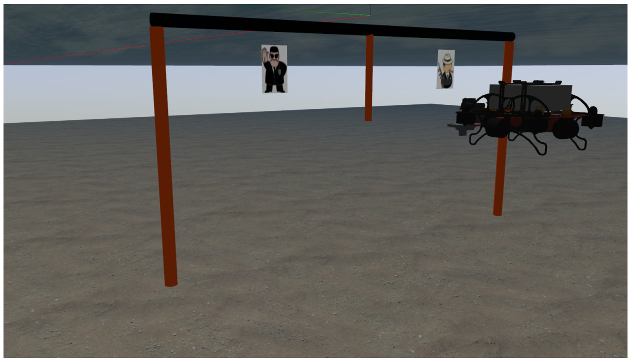


Figure 2.16 Gazebo scene setup for the gate task

5. Mission Planner

We used Smach as a Mission planner to divide a given task into a structure of subtasks. It allows us to compose and coordinate complex robot capabilities to robust robot applications. The nodes in each task are operated through messages published on different topics. The subtask to be performed next is determined by the message from the current subtask or the subtask just executed. The current task, if executed successfully, publishes messages that lead the robot further to another task in the task structure. In case any of the tasks fails, the corresponding defined action is taken.

III. EXPERIMENTAL RESULTS

Since we had very limited access to the pool because of this ongoing pandemic situation, Gazebo based simulations helped us to draw some insights about our chances of succeeding in the tasks. We had also planned on using YOLOv3 based object detection in the real

situation, however because of the ongoing situation we could not train a custom YOLO detector in a remote environment. But since we have used this algorithm in some of our previous vehicles, we are pretty confident about its performance. So for testing in simulations we have used OpenCV based object detection.
In order to make some valid predictions about our success rates it was necessary to model the vehicle as well as the environment as accurately as possible. To test the robustness of the algorithms in real time scenarios it was important to perform simulations in as different environments as possible. Also, simulating the sensor noises was a crucial part of this stress testing process.

Based on the simulations and various tests performed, as well as from our previous experiences, we can conclude that our chances of successfully completing the tasks is as follows:

- For the gate task along with style it would be approximately 95%,
- For the buoy task as well as the path markers, we are estimating a success rate of 100%, since we have performed these tasks previously and have simulated them also.
- We have also tested our marker droppers in underwater environments during past competitions as well as simulated it on Gazebo, hence we are confident about completing the task without lifting the lid with 80% success rate.
- We are quite confident with our acoustics navigation system and predict an 80% chance of successfully detecting the pinger to a sufficient distance such that the image recognition system can take over.
- Since we have tested the torpedo in underwater environments previously and based on that we have improved the torpedo design, we are predicting a success rate of 70% while shooting through the bigger opening and a success rate of 60% while shooting through the smaller opening since we haven't tested our improve torpedo design underwater.
- We have tested the gripper mechanism previously, but since the margin of error in the task is significant, our confidence of successfully completing the task is about 40%.

Dropper Testing:

The team successfully tested the detect and drop code for the vehicle using a prototype model of the dropper in the initial phase of testing.

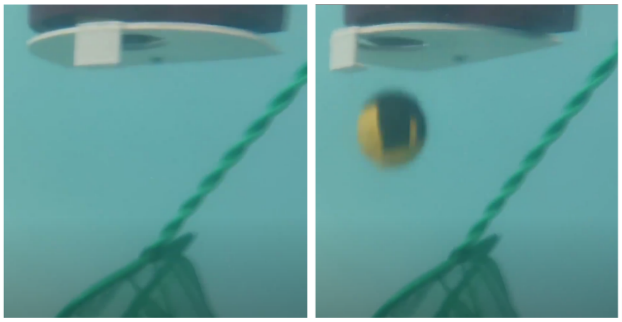
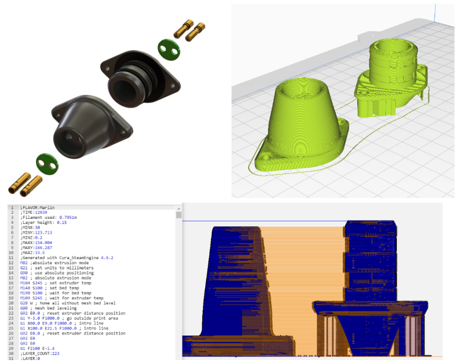


Figure 3.1 Successful dropper testing

Power Connector for Underwater Application

Because of the high hydrostatic pressure and corrosive nature of the marine environment, it is difficult to secure and reliable electrical connections. IP67 and IP68 connectors have to be used for transmitting electrical signal and power. Therefore, the reliability of the whole system during deployment, lifetime and maintenance becomes dependent on its connector. For quick testing, we designed an underwater connector which allowed us to make waterproof connections for quickly disconnecting the vehicle.

Fabrication. Metal pins or the bullet connectors were soldered on a custom-designed PCB and assembled with the rest of the body. Marine-grade epoxy resin was used to seal the bullet connectors inside the plastic body. The issue with 3D printing a waterproof connector is that since the part is produced by a continuous stacking of polymer layers, the resultant parts are highly porous. The connector body was post-processed to tackle the issue by treating it with Acetone (C3H6O) vapours.



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;Filament used: 8.7951m
;Layer height: 0.15
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;MINZ:0.2
;MAXX:154.004
;MAXY:166.287
;MAXZ:33.5
;Generated with Cura_SteamEngine 4.6.2
M82 ;absolute extrusion mode
G21 ; set units to millimeters
G90 ; use absolute positioning
M82 ; absolute extrusion mode
M104 S245 ; set extruder temp
M140 S100 ; set bed temp
M190 S100 ; wait for bed temp
M109 S245 ; wait for extruder temp
G28 W ; home all without mesh bed level
G80 ; mesh bed leveling
G92 E0.0 ; reset extruder distance position
G1 Y-3.0 F1000.0 ; go outside print area
G1 X60.0 E9.0 F1000.0 ; intro line
G1 X100.0 E21.5 F1000.0 ; intro line
G92 E0.0 ; reset extruder distance position
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G1 F2100 E-1.4
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Figure 3.2 Watertight connector design and analysis

Gripper testing:

The successful testing of the claw mechanism was done, later on we optimised the mechanism for better gripping design and reduced the claw weight, thus improving the overall performance. We plan to test the force sensing using the mapped force values with the current values in the coming days.

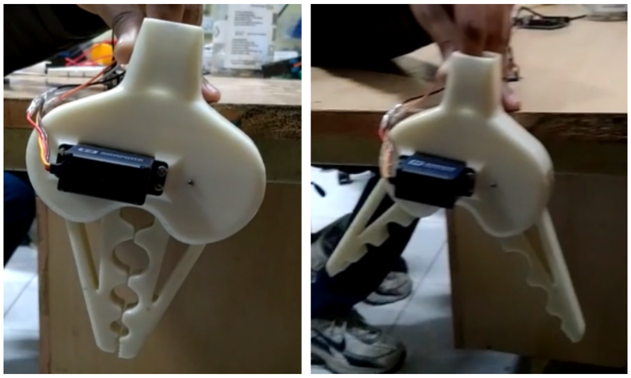

Figure 3.3: Prototype claw mechanism testing

IV. ACKNOWLEDGEMENTS

DTU AUV would like to thank and express gratitude towards everyone who has come together and helped us to make the project a huge success. We'd like to express our sincerest thanks to our faculty advisor Dr Ajeet Kumar and his guidance on the design considerations. Moreover, the team wouldn't have been able to function without its cold sponsors who generously funded us and helped us acquire all the resources that were required during the many stages of the project. Finally, we would like to thank the knowledgeable and resourceful network of DTU AUV alumni who made themselves available for advising and sharing their valuable experiences and helping us circumvent multiple roadblocks that one faces while designing a vehicle.

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APPENDIX A: COMPONENT SPECIFICATIONS

Component	**Vendor**	**Model/Type**	**Specs**	**Cost**
Buoyancy Control	NA	NA	NA	NA
Frame	In House	Plane truss structure 3D printed attachments	4mm Aluminium 6061 T6 sheets 3D Printed ABS	$150 $81.20
Waterproof Housing	Hammond Hammond Polycase	1554YA2GYSL1554C2 GYCL AN-07F-01	IP68 rated, Polycarbonate IP68 rated, Polycarbonate IP68 rated, Aluminium	$108 $27 $33.69
Waterproof Connectors	Blue robotics	Potted Cable penetrator	Quantity: 20,M-10 thread, 6mm cable	$100
Thrusters	Blue robotics	T200	Quantity: 8,Operating Voltage:7-20V, Full Throttle Current(@20V):32A	$1432
Motor Control	Blue Robotics	ESC for T200	Quantity:8,7-26 volts (2-6S)	$216
High-Level Control	Arduino	Mega 2560	6-20V,54 digital I/0 pins,16 analog pins, Clock speed:16MHz	$24.30
Actuators	Hitec	Servo HS5646WP	IP67, Torque:11.3-12.9 Kg-cm^2/s^2	sponsored
Battery	Tattu	Tattu 14.8V 25C 4S 10000mAh Lipo Battery Pack	14.8V 25C 4S 10000mAh	$350
Regulator I	Robu	LM2596S	Quantity:2,Input Voltage:3-40V,Output Voltage:1.5-35V(Adjustable)	$1.60
Regulator II	Mini-box	DC-DC NUC	12V or 19V selectable output, 6A peak	$59.5
CPU	Intel	NUC7i7BNH	12-19 VDC,3.50 GHz,1.21Kg	$300
Internal Comm Network	N/A	N/A	N/A	N/A
External Comm Interface	N/A	N/A	N/A	N/A
Inertial Measurement Unit (IMU)	Bosch	BNO055	9 Axis, supply voltage:2.4-3.6V, Range:125-2000 deg/s	$10.70
Hydrophones	Teledyne	Reson TC-4013	Quantity:3,1 Hz-180KHz ,depth:700m	$538x3
Acoustics I	Maxim	MAX11043ATL	5V, 4-channel, 16-bit, simultaneous-sampling ADCs	$157.50

Acoustics II	Texas Instruments	LAUNCHXL-F28379D	200 MHz dual C28xCPUs and dual CLAs	$33.80
Vision	Logitech	C930E	Full 1080p HD video at 30 frames per second	$ 130
Pressure sensor	Blue Robotics	BAR30	300m depth	$72
Current sensor	Robu	ACS712	Measure Current Range: -30A ~ 30A	$1.90
Voltage sensor	Robu	Voltage detection sensor module	Voltage detection range: 0.02445V - 25V DC	$1.10
Manipulator	In House Developed	Gripper Dropper Torpedo Launcher	3D Printed ABS	$24.33 $13.10 $15.73
Algorithms: vision	N/A	OpenCV, YOLOv3	Underwater Single Image Dehazing, YOLO Object Detection, Distance Estimation using triangulation, ORB	N/A
Algorithms: acoustics	N/A	TDOA	Hyperbolic positioning	N/A
Algorithms: localization and mapping	N/A	OpenCV	Localisation using vision algorithms	N/A
Algorithms: autonomy	N/A	Smach	Finite State Machines	N/A
Open-source software	OpenCV, YOLOv3, Robot Operating System, Smach, Gazebo, Python, C++			
Team Size (number of people)	29			
Expertise ratio (hardware vs. software)	19/10			
Testing time: simulation	170 hours			
Testing time: in-water	4 hours			
Inter-vehicle communication	N/A			
Programming Language(s)	C++, Python			

APPENDIX B : OUTREACH ACTIVITIES

Each year DTU AUV attends and organizes many workshops to reach out to the community. Through these exhibitions, DTU-AUV tries to reach young and insightful minds to take up robotics.

Presenting our vehicle to Hon'ble Chief Minister:- Arvind Kejriwal

The team organised a Machine Learning and Artificial Intelligence Workshop. The program implemented a well-researched plan to spread AI talent at global tech hubs for applications in practical decision-making. In this workshop, the basics of modern AI, as well as some of the representative applications of Artificial Intelligence, were covered.

ML and AI workshop organised by DTU-AUV

The team believes in spreading awareness about what advancements are taking place in the fields of science and technology. Every year we conduct a number of school workshops to promote such activities and also give school students a sight of exactly what kind of environment they face when they go for higher studies.

Workshop organised for school students

Tricky circuit competition organised by DTU AUV

We have organised workshops in collaboration with NGOs to provide an opportunity to students with limited means to develop a knack for science, enhance their problem solving abilities, analytical thinking and practical skills to support their intellectual growth.

Workshop organised for students with limited means

Workshop organised in RP public school , Rohini