Technical Design Report of Matsya 6, Autonomous Underwater Vehicle

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***Abstract*—Matsya, is a series of Autonomous Underwater Vehicles (AUVs) being developed at the Indian Institute of Technology (IIT) Bombay with the aim of delivering a research platform in the field of underwater robotics and promoting autonomous systems. Major architectural changes have been made to the subsystems by designing them from the perspective to handle tasks in real time. Some of the key features include improved heat dissipation, debug board, competition friendly mission planner.**

Fig. 1: Matsya 6

I. Competition Strategy

The objectives and challenges at RoboSub 2020 consists of challenging environment manipulation. The team approached the competition with a major focus on error-minimized reproducibility of the new vehicle design and increased reliability of Matsya's performance in tasks at RoboSub. A critical analysis was done to address the heating issue in the main hull which led to multiple electrical failures. The problem was addressed by developing a proper heat dissipation mechanism for the two main sources: Base plate modification for GPU & New ESC hull for the ESCs. The vehicle design also saw significant changes in positioning of components as compared to its predecessor leading to a smaller vehicle with better control.

This year, we set our target as the G-man and its related tasks, due to the very well-characterized images associated with them. In order to maximize our score, we would attempt all bonus tasks: starting at a random position, performing style moves as we pass through the gate, opting for the random pinger, shooting through both the ellipse and trapezium of the torpedo task, dropping markers in the closed section of the bin, and surfacing-up through the octagon with a bottle.

In order to achieve the above with maximum confidence, we have made some major improvements in the software sub-system. We have greatly improved our controller tuning for accurate setpoint achievement. This is vital in the Torpedo task and in picking up bottles, as the maximum permissible error margins here are small. We have fixed the issue of the cameras getting disconnected mid-run by implementing our very own custom camera drivers. Also, last year's mission planner was feature rich but very complex, making it less reliable as we had to provide it with a multitude of parameters just minutes before a run, making the process error-prone. Hence we have greatly simplified the planner this year.

II. VEHICLE DESIGN

Mechanical Sub-system

Core philosophy behind design of Matsya 6 - Compactness, Modularity, Reliability. The mechanical design can be bifurcated into Hulls and Frame (Structure and Component Positioning). A total of 8 thrusters have been used to provide all 6 DoFs to the vehicle. The vehicle is also equipped with various manipulation systems (Arm, Gripper, Torpedo Shooter, Marker Dropper).

Hulls: *Main Hull:* The vehicle has a main hull which houses all major electronics. The new main hull design includes features like layered and backplane electrical stacking, and a redesigned base-plate to ensure proper heat dissipation (direct GPU mounting on the baseplate to improve heat transfer).

ESC Hull: A new hull was designed housing all the ESCs (Electronic Speed Controller) and elec circuitry in order to reduce the volume occupied by the ESCs and majorly to improve the heat dissipation due to the 8 ESCs, which caused multiple electrical failures in the past iteration of the vehicle. Interdisciplinary discussions and multiple design sketches led to a rectangular shaped hull having grooves in the walls and the base plate for steady contact of ESCs with the hull surface for continuous cooling from the surrounding water. The PWM signal wires were brought in through a separate penetrator in order to minimize the interference and attenuation. This resulted in a reduction of 60 % volume occupied by ESC and elec circuitry as compared to the last iteration and this space in the main hull was used to accommodate the newly made boards by the electrical division.

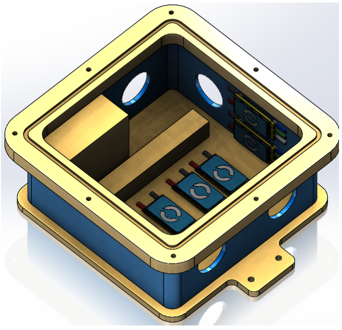


Fig. 2: New ESC Hull

Battery Hulls: Batteries are stored in cylindrical battery hulls. Team's experience with cylindrical hulls (Matsya 4) simplified the designing and analysis process. This design helps in reducing disassembly time considerably, increasing the ease and speed of taking the batteries out (for recharge purpose). It also increases modularity which can in turn help in C_g-C_b balance. A dome structure is added on the front-facing plane of the hull to reduce drag.

Camera Hulls: Matsya-6 has two cameras each enclosed in a cylindrical camera hull mounted on the front and bottom of the vehicle to cover maximum field of view

Frame: A skeleton type frame has been designed to reduce weight without compromising on strength. It also has handles to transport the vehicle by hand, and additional handles at the rear end for the diver. The parts of the frame on which heavy parts are mounted are designed such that it has a high load bearing capacity in the vertical direction. The parts on which thrusters are mounted is designed based on the loading the thruster would be exerting on it.

Manipulators: To perform all possible tasks in the competition Matsya-6 is equipped with various manipulation systems namely:

Arm & Gripper: A 1-DoF arm with humerus and ulna connected by re-volute elbow joint with a split-finger gripper actuated pneumatic air cylinder.

Torpedo Shooter & Marker Dropper: High-pressure pneumatic actuators are used for shooting torpedoes, and marker dropper mechanism with reloading capacity.

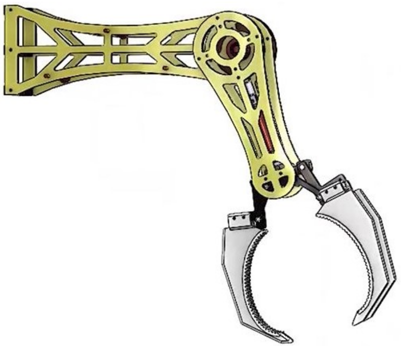
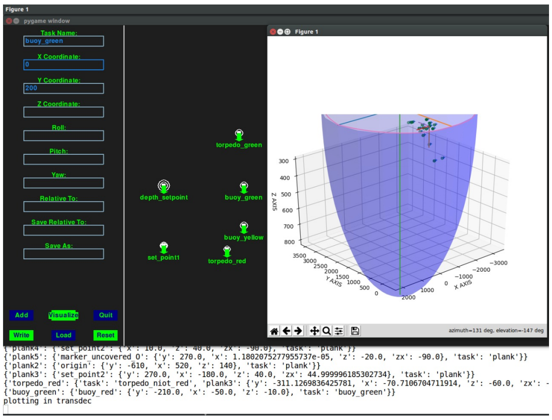


Fig. 3: Arm & Gripper Assembly

Software Sub-System

Camera Drivers: We have made the switch from a third party (AVT Vimba) driver to a brand-new, custom, in-house implementation. This has led to a 270% increase in maximum achievable frame rate (52Hz now vs 14Hz earlier). While the earlier driver could not handle a shutdown of the cameras (which was caused by either power failure/USB connection issues), the new one seamlessly reconnects to the cameras and restarts publishing the video feed on the corresponding ROS topic. Our implementation also allows us to set various parameters like Absolute Frame Rate, Exposure and Gain.

Mission Planner: Our previous implementation, the most powerful we have ever made, needed multiple parameters to be tuned just before a run. This made parameter tuning prone to human error, especially in the high-stress RoboSub competition. Hence, we have simplified that planner and the decision making process is almost linear. Minimal parameters need to be tuned just before deployment, making it very competition friendly. It inherits task-grouping from the previous design. We have also implemented a *pretty printer* for improved clarity in the outputs of the planner.



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Roll:
Pitch:
Yaw:
Relative To:
Save Relative To:
Save As:

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plotting in transdec
```

Fig. 4: Map GUI tool

Auto Tuner for Controller: To auto-tune the controller parameters, we have implemented an algorithm that studies Matsya's motion and uses a binary search inspired algorithm to tune thruster correction values. These values take into consideration the offset caused by the center of mass of Matsya not being in line with the centre of application of torque. We have also automated our PID tuning process, achieved by using heuristic methods to derive a model followed by an evolutionary algorithm that identifies optimal PID gains.

GUI Tool for Map: As there are often human errors when entering coordinates of tasks for the map before the runs at RoboSub, we have created a GUI tool that allows the user to add tasks, dynamically visualise them in 2D and 3D, and then save the map as a YAML file when satisfied.

Path Planner and Path Follower: In the navigator package, a novel path planning algorithm has been implemented which plans the path of Matsya across the map from start to end, taking into consideration the location of obstacles in the map. It uses breadth first search paired with some simple constraints and heuristic functions. This path is then passed to the new and improved Path Follower which allows the vehicle to move along the specified trajectory, adhering to the given velocity constraints. It helps Matsya navigate trajectories smoothly, without taking any sharp turns.

Electrical Sub-system

ESC Hull : Continuing from the Mechanical Section of the ESC Hull, many new features were added to the system when ESCs were separated from the main hull. This includes a custom made power distribution box for eliminating wire clutter in the hull, a Mechanical Latch Relay to implement hard Kill by directly disconnecting the battery in case of failures and real-time current and PWM monitoring for each ESC, so that any malfunction of the thrusters is known to the system and the operator for better debugging.

Wiring : Also, this time, wire routing and management was taken with utmost care so that the wiring remains comprehensible after the vehicle is assembled. This included taking an account of all the wires and their bending radius, heating properties and other parameters in the vehicle design itself, so that debugging and assembly of both Main Hull and ESC Hull are super smooth.

Electrical Board Stack : We also equipped the main elec-stack of MATSYA 6 with a lot of new features offering controlled redundancy and debug capabilities to mitigate in-run failures.

1. A new Debug board is designed that captures data from all the sensors on-board including the electrical stack itself, PWM channels, thruster current values (from ESC Hull) and the motherboard. The data is logged on an SD card for analysis later on. And it's also sent to the motherboard for any real-time decision to be made on an event and at the same time displaying the status on an LCD screen for easier debugging in the development phase. We also added Status LEDs to get visual feedback about the vehicle state (scanning, or transition or execution) during the autonomous run.

2. The GPIO board is equipped with two different micro-controllers each capable of controlling the entire vehicle independently ensuring dual redundancy and user-selected complexity. The Debug Board along with the GPIO facilitate a mutual feedback and restore system in case any one micro-controller fails.

3. The power board generates and supplies all the different voltage levels required for all the sensors, other boards and the motherboard. This year the number of mutually exclusive toggle lines was increased from four to eight for better control of the power across the vehicle, implementing other features like reverse battery and over-voltage protection as well. The Backplane provides one-point interfacing of the electrical stack with the sensors and the motherboard.

4. The Backplane Board was redesigned to house the Debug Board and all its necessary features. It now houses the Power, GPIO and Debug board and ensures easy connections and routings to all the other peripherals and sensors.

III. Experimental results

Simulation-based testing is the need of the hour during this pandemic. We have expanded our simulation package's capabilities by incorporating the UUV simulator. It allows for more accurate simulations with its variety of plugins that model underwater hydrostatic and hydrodynamic effects, thrusters and sensors, hence allowing us to compensate for the lack of in-pool testing.

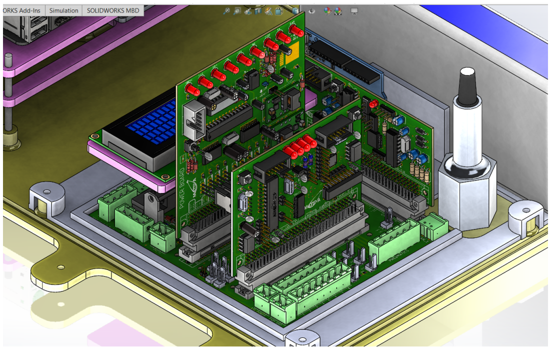

Fig. 5: Elec stack of Matsya 6

Simulation Results

Models of this year's tasks were made using Gazebo's model editor. OpenCV-based detection has been used as our lab's resources are not accessible due to the COVID-19 pandemic and we can hence not run our default YOLO network. OpenCV suffices here because of the ideal conditions in the simulator. However, in real life testing, it would not suffice and would be entirely replaced by ML-based detection and classification.

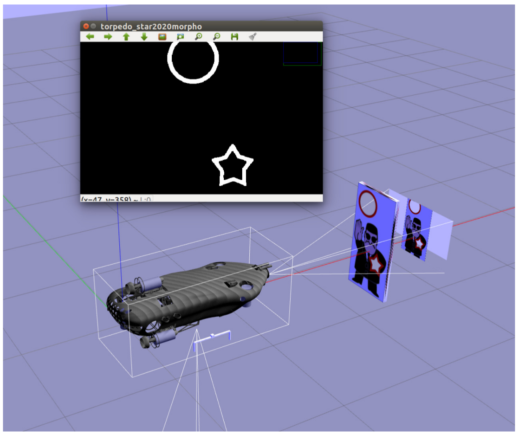

Fig. 6: Gazebo simulation of Torpedo task

1) Gate Task: The gate task this year has been made much easier with the inclusion of images at the gate, as we can now detect the larger images rather than the thin pipes making the gate.

Estimated probability of successfully completing the gate task: 100%

2) Buoys task: The current buoy is planar as compared to last year's, more difficult, prismatic buoy. As we successfully completed last year's buoy, we are 100% confident of completing this year's version.
3) Bin Task: As there are now more visual features to work with (images on the bins have highly characteristic colors), a large improvement is expected in the performance on the vision side. The probability of success for the open bin task is around 90%, while it is estimated to be 70% for the closed bin task.
4) Torpedo Task: The accuracy of detection from the vision side is again expected to greatly improve because of the starkly different shapes and red borders. Our main source of error is in centering the torpedo barrel on the task, as our error in positioning has to be lesser than 5cm. Our simulations show that shooting through the ellipse has a 80% chance of being successful, and shooting through the trapezium, a 70% chance.
5) Pinger Task: The vehicle has a very high accuracy of pinger detection and can easily reach within 60cm of the pinger. The success rate is about 90%.
6) Octagon Task: Increased gripping area of the arm has increased the chances of picking up a bottle. Hence we estimate the chance of picking up a bottle to be around 50%. As the tables are well-characterised, once the bottle has been grasped, placing it on the table or rising up through the octagon with it have more than a 90% chance of success.

The Mechanical Division performed extensive simulations and experiments to justify the design changes that were made.

Thermal Analysis of the Main Hull

1) Analysed the heating issue of the Main Hull by performing CFD simulations on ANSYS Fluent
2) Conducted proof-of-concept experiment on the temperature dependence of the heat source on flow rate
3) Redesigned the baseplate to mount the GPU directly onto it, ensuring peak temperatures below the safety limit of 95°C

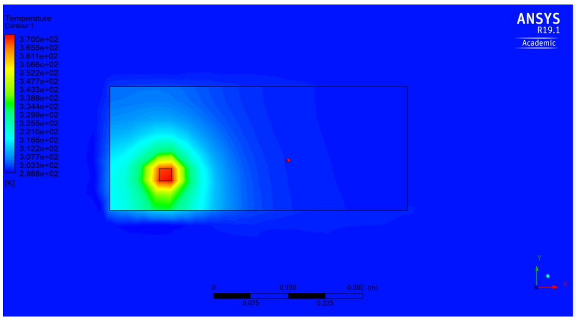

Fig. 7: Temperature Distribution of the Base-plate

Pressure Analysis of Hulls

We have ensured the strength of the pressure hulls by running simulations on ANSYS Static Structural. Thus, finite element analysis is used to check the safety factor and deformation in hulls when pressure equivalent to that exerted by water at target depth is applied.

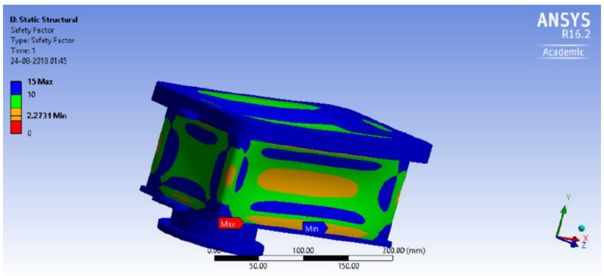

Fig. 8: Safety factor of DVL Hull at 20m depth

IV. ACKNOWLEDGEMENTS

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We sincerely appreciate the generous support from our sponsors. Special thanks to our vendors Blue Robotics and Teledyne RDI for their support in case of technical problems.

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Appendix A: Component Specifications

Component	**Vendor**	**Model/Type**	**Specs**	**Cost**(if new)
Bouyancy Control	Designed In-House	Dead Weights & Foam	-	-
Frame	Designed In-House	Aluminium & Delrin	4 kg	800 USD
Waterproof Housing	Designed In-House	Aluminium Hulls w/ Acrylic Endcap	8 Hulls weighing 22 kg Depth Rating : 70 ft	2100 USD
Waterproof Connectors	Designed In-House	Aluminium	24 connectors weighing 1.5 kg in total	150 USD
Thruster	Blue Robotics	T200	11 and 9.5 kgf forward and backwards	1600 USD
Motor Control	Blue Robotics	Basic R3 Version	30A PWM controlled brushless motor speed controller	200 USD
High Level Control	Microchip Technology	Atmega 328P and 32M	Low Power CMOS 8-bit RISC Microcontrollers	15 USD
Actuators	Janatics	A51012025O	Stroke Length: 25mm	30 USD
Battery	Tattu	LiPo Battery	4 Cell and 16000mAh x 2	400 USD
Converter	Texas Instruments	PTN 78060	6A wide input output Adjustable switching regulator	50 USD
Regulator	Mini-Box	M4ATX	High efficiency 250W output, $< 1.25mA$ standby current	80 USD
CPU	Intel	Intel i7	i7 8700, 8GB RAM	-
GPU	Nvidia	GeForce GTX 1660ti	GDDR5, 6GB, 120W	300 USD
Internal Comm Network	Microchip Technology, CAN USB	MCP 2515, MCP 2551, CAN USB	1 MB's operation limit	150 USD
External Comm Interface	-	Ethernet	10-100 Mb/s	-
Programming Languages	C++, Python	-	-	-
Compass	-	-	-	-
Inertial Measurement Unit (IMU)	Microstrain	GX5	-	-

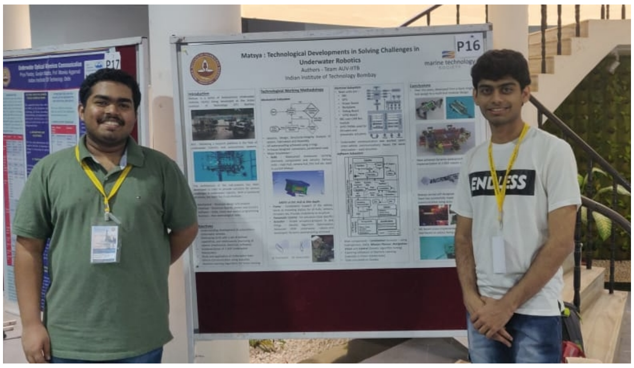
Doppler Velocity Log (DVL)	Teledyne	Explorer DVL	-	-
Camera(s)	Allied Vision	MakoG-243	-	-
Hydrophones	Teledyne	RESON Underwater TC 4013	-	-
Manipulator	Designed In-House	-	1 DOF servo-operated arm, pneumatic driven end-effector	300-350 USD
Algorithms: Vision	YOLO v3	-	Parallel and Sequential processing, lens formula	-
Algorithms: Acoustics	FFTW	Time difference of arrival	Filtering in frequency & time domain	-
Algorithms: Localization and Mapping	Orocos BFL	Extended Kalman Filter	EKF applied on position found by integration of DVL velocity	-
Algorithms: Autonomy	-	State Machine & Mission Planner	Probabilistic (or Finite) state machine for mission planner, designed in-house	-
Team size	45	-	-	-
HW/SW expertise ratio	2:1	-	-	-
Testing time: simulation	200 hrs	-	-	-
Testing time: in-water	40 hrs	-	-	-

APPENDIX B: OUTREACH ACTIVITIES

The AUV-IITB Team, each year attends many workshops and/or exhibitions to reach the community. It is through these exhibits the team encourages young school as well as high school students to take up robotics. The team demonstrates working of the AUV followed by a detailed seminar and a questionnaire session to motivate students and increase their knowledge about AUVs and robotics in general.

Prime Minister of India, Shri. Narendra Modi with Matsya 4 at IITB

We also participated in MTS TECHSYM-2020's Students' Technical Symposium On Advances In Engineering And Technology, held at IIT Madras, where we interacted with professors and students from all across the country who are working on various maritime technologies. We presented a poster highlighting the various advances made in Matsya, with the hope of encouraging other AUV teams along their journey. We received a special mention for the same.



Presenting our poster at MTS TECHSYM, IIT Madras

The team assisted in conducting a week long workshop for the student technical team from the Bannari Amman Institute of Technology, Tamil Nadu in the design and manufacture of AUVs.

Apart from this, the joy it brings to others, especially young enthusiastic school students (for example students of Witty International School shown in photo) is a rewarding experience and motivates the team further to work harder and continue to make more developments.

School children at our lab

The research that was done by the team also helped several students in their Masters/BTech projects on topics like Control of Overactuated Nonlinear Systems, Navigation of Unmanned Vehicles, Design of a 2-Link gripping mechanism, and Sunlight flicker removal. This further fuels the team to work harder and deliver results.

The team also mentors quite a few other teams from India, who are keen on making AUVs, like IEM Kolkata, KJ Somaiya College of Engineering, Mumbai, Sahyadri College, NIT Rourkela, IIT Kanpur and VIT Pune. The team guides them through the overall procedure of making an AUV, the importance of communication and documentation and the process of acquiring funds for making AUVs in their respective colleges.