Technical Design Report of Matsya 6B, Autonomous Underwater Vehicle

Nakul R, Andrews V, Aditya H, Shubham T, Nayan B, Nandagopal V, Ruchir C, Sidharth M, Tejas B, Devansh J, Ayushi G, Parvik D Shiv M, Aayush S, Nirmal S, Vikram A, Sudarshan G, Vinayak S, Sabhya S, Hastyn D, Kalp V, Sankalp B, Sankalp P, Govind S, Lyric K, Raavi G, Rishabh R, Sarthak R, Kaustubh C, Advait R, Pratik S, Abhimanyu R, Shivam A, Omkar P, Ammar B, Abeer M, Sunandinee M, Sanya A, Nandini K, Aditya S, Anuj B, Mayank B, Kartik C, Anurag D, Kaushik V, Harsh A, Yashas S, Nimish S, Pranav J, Archit S, Rathin A, Aaryan D, Nivesh M, Arushi B, Archit G, Sameer M, Tanvi P, Surbhi G, Chandrika A, Suyash W, Shumail M,

Faculty Advisors: Prof. Leena Vachhani and Prof. Hemendra Arya

***Abstract*—Matsya is a series of Autonomous Underwater Vehicles (AUVs) being developed at the Indian Institute of Technology (IIT) Bombay to deliver a research platform in underwater robotics and promote autonomous systems. Significant architectural changes have been made to the subsystems by designing them to handle real-time tasks. After almost two years, the vehicle was tested in the swimming pool with the main aim of improving the reliability of the existing features on the vehicle. Some key additions include improved heat dissipation, the simulation of an underwater localization system, and revamped controls and path planning. This paper presents an insight into the team's design process for the latest autonomous vehicle, *Matsya 6B*, and the analytical methods that the team used for the prototyping and development of the vehicle, including structural simulations, hydrodynamics analysis, underwater data transmission models, path planners and strategies to optimize the design.**

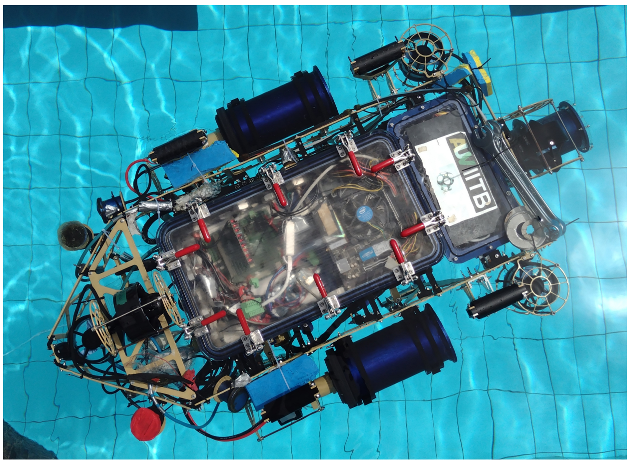


Figure 1: Matsya 6B

I. Competition Strategy

The objectives and challenges at RoboSub 2022 involve challenging environment manipulation, especially since it is the first time after two years that the competition will be held offline. The approach toward the competition minimizes errors and increases the vehicle's reliability in completing each task.

Since we have options to use darknet and OpenCV for vision, we will decide between G-Man and Bootlegger depending on the testing results. Since Matsya 6B has all the features required to try every task, attempts will be made to secure the maximum number of points in each task by attempting the highest-scoring combination given the time constraints. Having encountered and completed the gate, pinger, buoy, and torpedo tasks in previous years, the team is confident about completing these tasks.

Buckling analysis of all the hulls has been performed to ensure that they would not severely deform or collapse even up to the depth of 100m. Topology optimization has been implemented to reduce the weight of the components. It is an effective technique to optimize the structural design of the parts while maximizing the stiffness. Previously, the main hull of Matsya 5 was prone to heating issues, which eventually led to multiple electrical failures and forced the vehicle to shut down mid-run. This problem is addressed in Matsya 6B by developing heat dissipation mechanisms for the Graphics Processing Unit (GPU) and the Electronic Speed Controllers (ESCs), which are the primary sources of heat in the vehicle.

The vehicle was tested in the swimming pool after almost two years when the COVID-19 restrictions in India were relaxed. Due to this, many of the features added in the last two years had to be tested. This made our main aim to spend more time on testing and improving the reliability of the existing features on the vehicle.

This year, only one vehicle will be deployed, the Matsya 6B, which is capable of attempting all the tasks in RoboSub. We plan to approach all the bonus tasks starting with the coin flip (With Moxy) task. After the coin flip, we will attempt the 'Choose your side' - gate task along with the style aspect of this task due to the stability of the electrical stack inside the main hull of the vehicle. Then, the vehicle will bump the appropriate buoy with the chosen side as a part of the 'Make the Grade' task. Before bumping into the chosen side, the vehicle will perform a horizontal scan to identify and localize the buoy's position. After this, the vehicle will do the 'Collecting task' and lift the cover and drop markers in the proper bin. The bins will be detected using an outward-moving spiral motion, and feedback will be given to the arm on the handle's location. We will then move on to the 'Survive the Shootout' task, where the vehicle will attempt to fire the torpedoes through both the larger and smaller opening. Finally, the vehicle would attempt the 'Cash or Smash' task and surface through the octagon after placing the bottles on the proper table.

II. Vehicle Design and Analysis

A. Mechanical Subsystem

The mechanical design can be bifurcated into Hulls and Frame (Structure and Component Positioning). A total of 8 thrusters have been used to provide active control of all 6 degrees of freedom to the vehicle. The vehicle is also equipped with various manipulation systems (Arm, Gripper, Torpedo Shooter, Marker Dropper). Any potential design undergoes an iterative procedure involving prototyping and critical design reviews until all design requirements are met.

The mechanical subsystem ensures the robustness of the design by running various analyses like structural, hydrodynamic, and thermal studies of the vehicle. The following sections present the work on improving the structural integrity of hulls, drag reduction systems, thermal management solutions, and overall optimization of space and weight of the vehicle.

Hulls: All hulls are waterproofed using end-caps, o-rings, connectors, and penetrators for the electrical routing. Static structural and linear buckling analyses are performed on each hull and the entire vehicle using the Finite Element Method in ANSYS. Thus, ensuring a safety factor of 2 and hull integrity up to a depth of 100m.

Main Hull: The vehicle has a main hull that houses all major electrical components. Al 6061 was used for the base of the main hull, whereas Al 5052 was for the side walls. This is due to the high malleability of Al 5052. A rectangular shape increases packing efficiency as all the electrical boards are rectangular. A counter sink was added to the base plate to ensure the GPU's temperature was within the operating limit, providing efficient heat dissipation through the walls using surrounding water. This ensured the peak temperature was limited to 40°C. Steady-State Thermal analysis was performed using ANSYS on the base plate to confirm this.

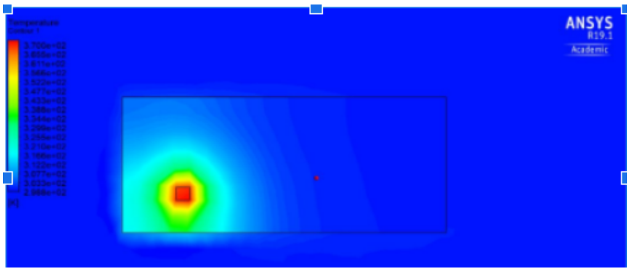
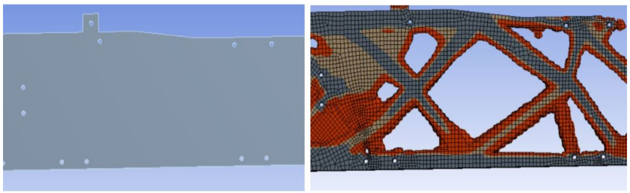


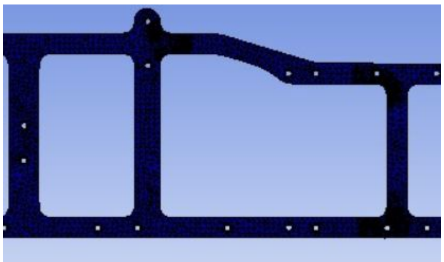
Figure 2: Temperature Distribution of the base-plate.

ESC Hull: The ESCs were moved to a separate hull to reduce the temperature in the main hull. This ESC hull was designed to occupy minimal space and ensure good contact between the ESCs and the hull walls to dissipate heat effectively.

Frame: The skeleton-type frame is 5mm thick and is made of Alloy Al-6061. To maximize the stiffness while reducing weight, Topology Optimization has been applied to the frame. Topology optimization was performed by linking it with Static structural analysis on the frame of Matsya 6B. The initial geometry provided the strength that was more than necessary and had a very high safety factor. Therefore, the objective was to minimize compliance with a constraint to retain $\approx$ 50% mass of structure in topology optimization analysis. Using the output obtained from optimization analysis, the previous design was modified, successfully reducing mass by $\approx$ 48%. The safety factor has been verified to be greater than the threshold value by performing a static structural analysis.



(a) Initial Geometry of the frame (left). Each hole in this frame corresponds to a mounting point and supports the load of different hulls or parts of the vehicle.; Optimised geometry as a result of topology optimization (right)



(b) Static structural analysis of final modified geometry.
Figure 3: Topology Optimization

Actuators:

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

Arm & Gripper: A 1-DoF arm with humerus and ulna connected by a re-volute elbow joint with a split-finger gripper. The pneumatics are actuated using solenoid valves and a pressurized air tank.

B. Software Subsystem

The Software Stack of Matsya 6B has been developed on the Robot Operating System (ROS). The system is implemented as a single stack with various modules such as vision, navigation, controls, firmware and mission planning. Furthermore, the code was shifted from ROS Melodic to ROS 2, which now makes the stack cross-platform.

Design specifications of the stack ensure that it is extendable and generic. ROS helps in keeping the software modular, handling the Inter-Process Communication via messages and services. It is also generic enough to be plugged into other robotic frameworks. Figure 4 depicts the software architecture of Matsya 6B as described above.

The following sections present our work on software upgrades.

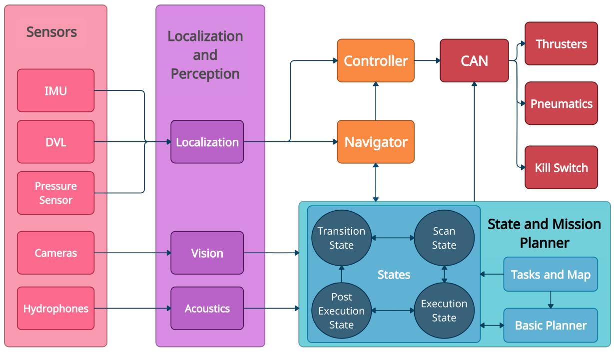


Figure 4: Software architecture of Matsya 6B depicting inter-package communication facilitated by ROS

Vision: Significant improvements were made to the vision package. The third-party AVT Vimba driver was replaced with a custom in-house driver, which is more robust and resilient to camera shutdowns. The peak frame rate has also been increased from 14Hz to 52Hz. Another significant improvement was the modularisation of our vision module, separating Darknet from the rest of the module and hence reducing compilation time. Moreover, we upgraded our machine learning architecture to Yolo v5, leading to noticeable accuracy and performance gains.

Acoustics: Previously, we had used the YDSE-based algorithm (Young's Double Slit Experiment) for pinger localisation- this year, we implemented the MUltiple SIgnal Classification (MUSIC) algorithm. It estimates the Direction Of Arrival (DOA) based on second-order statistics, now adding to our vehicle the capability of multi-pinger localization.

Path Planning: We implemented the Regular Hexagon Guided (RHG) method to address a shortcoming in our Artificial Potential fields-based path planning model. The vehicle was prone to getting stuck in the local minima of the artifical potential function- this was fixed via the RHG method, that assumes a regular hexagon around the obstacle from which it can navigate around said obstacle.

GUI tools: We streamlined our testing workflow by developing several GUI tools

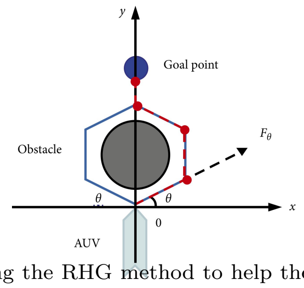


Figure 5: Using the RHG method to help the vehicle navigate out of a local minimum

that allow us to improve on our debugging. For instance, we developed a terminal utility that presents all the necessary information including battery status, sensor status and task success, in a single window- similarly, the new PID Tuning GUI plots the localisation data on a single screen, hence simplifying the tuning process. Furthermore, we developed a GUI for creating a map storing task positions with the use of a modern light-weight framework, Traits UI.

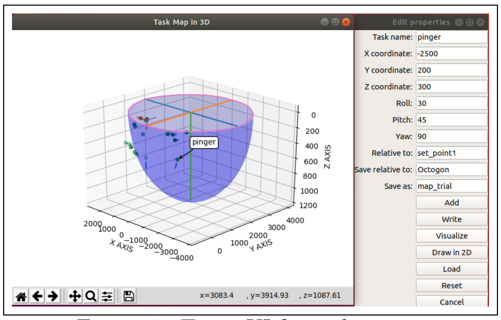


Figure 6: Traits UI for task mapping

C. Electrical Subsystem

The electrical subdivision of the team connects the software and mechanical subsystems by powering them and interfacing 13 nodes using different communication protocols. The main electrical stack includes 4 electrical boards, an SBC (Serial Board Computer), a GPU, ESCs (Electronic Speed Control), and other sensors and supporting circuits. Figure7 depicts a flowchart of the electronics architecture.

Electrical Stack: The main electrical stack of Matsya 6B is equipped with many features that offer controlled redundancy and debug capabilities to mitigate in-run failures.

The GPIO board: The GPIO Board is responsible for handling digital I/O, generating 8 PWM signals for thruster control and controlling the 4 pneumatic actuators.

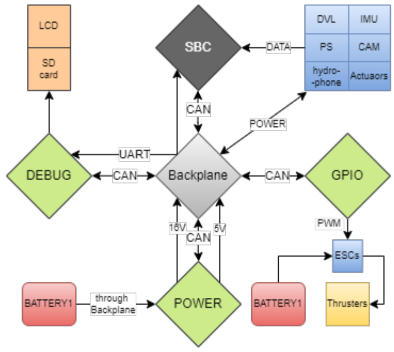


Figure 7: Electrical architectural diagram exhibiting the internal communication and power distribution

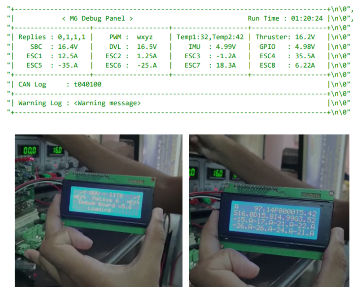


Figure 8: 'Sensor-status LCD-display' with sensors' voltages and currents

The Power board: The power board generates 8 toggleable (16V and 5V) power lines using 16V supply from battery and converting it to 5V regulated supply.

The Backplane: The backplane is the backbone of electrical stack ensuring plug and play of components. It connects all the sensors, SBC and other electrical boards to one another for communication and power distribution.

The Debug board: To ease and fasten the debugging process, we gathered all the parameters required from our past experiences and integrated the monitoring of these parameters into the debug board. It logs data from various onboard sensors to an SD card, allowing quicker correction of system errors and failures. It is equipped 'sensor-status LCD-display' (Figure 8), which can convey the state of operation of the vehicle visually. In case of CAN bus malfunction it act as backup mode of communication.

Sensors and Actuators: Matsya 6B has a central pneumatic system to actuate a gripper, marker dropper and torpedo shooter, two cameras, an IMU, a pressure sensor, a DVL and four hydrophones and a DAQ(Data acquisition system) with 0.5 MSPS sampling rate.

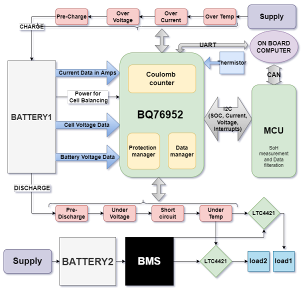


Figure 9: A detailed flowchart indicating all the functionalities of the prototype along with components of the BMS

Isolation of batteries: The vehicle has two batteries to ensure power isolation, safety, robustness and ease of operation. One battery is used for thrusters, while the other is used to power the electronic system.

Research and Development: *BMS:* We have developed a prototype of BMS (Battery management system) having a coulomb counter with probabilistic filters to determine SOC (State Of Charge); essential protections; Cell balancing and Battery switching.It is estimated that the BMS will help to increase the run-time of our current vehicle by 10%, increase the battery life by 20% and will add one more layer of robust protection.

SLAM(Simultaneous Localization and Mapping): SLAM is being implemented in the AUV to map uncharted areas and simultaneously track the vehicle's position and attitude. The algorithm was initially simulated for a 2-D motion, this was then extended to 3-D space. Several methods were explored for tuning the initial noise parameters of the filter. A separate EKF can calculate the orientation with the help of the data provided by the IMU housed in the AUV. Further research includes parallelizing the tasks in the algorithm so that the vehicle can localize faster.

III. Experimental results

We have developed an accurate and reliable controller for mapping target force to thruster output, capable of handling thrust imbalances and residual torque. Even in open-loop control, our vehicle can move in the desired direction in all 6 degrees of freedom. This has been created as a fallback in case our localisation sensor (the DVL) fails.

With access to the swimming pool, we were able to test most of the features we have added to the vehicle during lockdown. Trim weights and floats were added after the vehicle was assembled and tested to increase vehicle stability and make the vehicle neutrally bouyant. The temperature inside the main hull during pool testing was also found to be around 42°C due to the added countersink for the GPU.

This time we have integrated a new computer vision stack, boasting a high-performance optimized camera driver offering a peak performance of 52 FPS over the previous 14 FPS driver, upgraded object detection framework to the latest YoloV5 model, which gives a significant improvement in performance speed (2x faster) and accuracy.

To measure the battery life, various tests were conducted at the pool. The battery life was found to be 2 hours. The temperature of the battery hull was also measured and found to be around 40°C an optimum temperature for the functioning of the battery.

IV. Conclusion

Once the team received permission to do pool testing we focused on making the vehicle more robust and reliable. The software side of the vehicle was tested extensively to refine the computer vision system in place and make all our results reproducible. Matsya 6B is the most advanced vehicle the team has made and can quickly adapt and incorporate additional features without significant developmental changes. This was seen first hand in case of the gripper which adapted very easily to the open frame structure of the vehicle. The intermittent halts in testing due to surges in SARS-CoV2 cases did not water down our spirits as our team's philosophy of working with what we have came to the fore. Matsya 6B serves as an excellent platform for the team to further its research in underwater and autonomous robotics.

V. Acknowledgements

The team would like to thank the Industrial Research and Consultancy Centre of IIT Bombay for administrative and monetary support during the project and for helping us participate in RoboSub 2022. The support of the Dean R&D's office was crucial in the successful execution of the project.

Appendix A: Component Specifications

Component	Vendor	Model/Type	Specs	Cost (new)	Status
Bouyancy Control	Designed In-House	Dead Weights & Foam	-	-	Installed
Frame	Designed In-House	Aluminium & Delrin	4 kg	800 USD	Installed
Waterproof Housing	Designed In-House	Aluminium Hulls w/ Acrylic Endcap	8 Hulls weighing 22 kg Depth Rating : 70 ft	2100 USD	Installed
Waterproof Connectors	Designed In-House	Aluminium	24 connectors weighing 1.5 kg in total	150 USD	Installed
Thruster	Blue Robotics	T200	11 and 9.5 kgf forward and backwards	1600 USD	Installed
Motor Control	Blue Robotics	Basic R3 Version	30A PWM controlled brushless motor speed controller	200 USD	Installed
High Level Control	Microchip Technology	Atmega 328P and 32M	Low Power CMOS 8-bit RISC Microcontrollers	15 USD	Installed
Actuators	Janatics	A51012025O	Stroke Length: 25mm	30 USD	Installed
Battery	SkyCell	LiPo Battery	4 Cell and 16000mAh x 2	400 USD	Installed
Converter	Texas Instruments	PTN 78060	6A wide input output Adjustable switching regulator	50 USD	Installed
FPGA	Xilinx	Zybo Z7-20	Programmable logic equivalent to Artix-7 FGPA, DDR3L memory controller with 8 DMA channels and 4 High Performance AXI3 Slave ports, 667 MHz dual-core Cortex-A9 processor	300 USD	Installed
Regulator	Mini-Box	M4ATX	High efficiency 250W output, $< 1.25mA$ standby current	80 USD	Installed
CPU	AMD	Ryzen 3400G (4C8T)	4 Cores (4.2GHz), 8GB RAM	-	Selected
GPU	Nvidia	GeForce GTX 1660ti	GDDR5, 6GB, 120W	300 USD	Installed
Internal Comm Network	Microchip Technology, CAN USB	MCP 2515, MCP 2551, CAN USB	1 MB's operation limit	150 USD	Installed

External Comm Interface	-	Ethernet	10-100 Mb/s	-	Installed
Inertial Measurement Unit (IMU)	Microstrain	GX5	-	-	Selected
Doppler Velocity Log (DVL)	Teledyne	Explorer DVL	-	-	Installed
Camera(s)	Allied Vision	MakoG-243	-	-	Installed
Hydrophones	Teledyne	RESON Underwater TC 4013	-	-	Installed
Manipulator	Designed In-House	-	1 DOF servo-operated arm, pneumatic driven end-effector	300 - 350 USD	Installed
Algorithms: Vision	YOLO v5	-	Parallel and Sequential processing, lens formula	-	Implemented
Algorithms: Acoustics	FFTW	Time difference of arrival	Filtering in frequency & time domain	-	Implemented
Algorithms: Localization and Mapping	Orocos BFL	Extended Kalman Filter	EKF applied on position found by integration of DVL velocity	-	Implemented
Algorithms: Autonomy	-	State Machine & Mission Planner	Probabilistic (or Finite) state machine for mission planner, designed in-house	-	Implemented
Open Source Software	OpenCV, Eigen, ROS, YOLO v5	-	-	-	Implemented
Team size	55	-	-	-	-
HW/SW expertise ratio	2:1	-	-	-	-
Testing time: simulation	250 hrs	-	-	-	-
Testing time: in-water	0 hrs	-	-	-	-
Inter-vehicle Communication	-	-	-	-	-
Programming Languages	C++, Python	-	-	-	-

Appendix B: Outreach Activities

Team AUV-IITB was presented a research paper on 'Design of Battery Management System for an Autonomous Underwater Vehicle' in "Oceans Conference & Exposition Chennai'2021" The paper focuses on optimally utilizing the battery capacity and implementing all the essential protections.

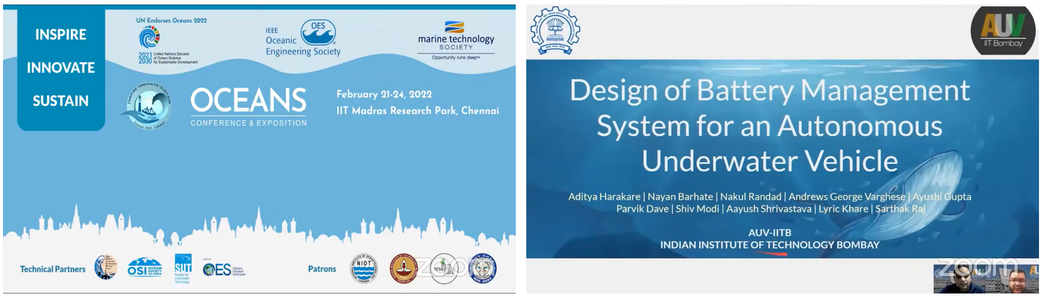
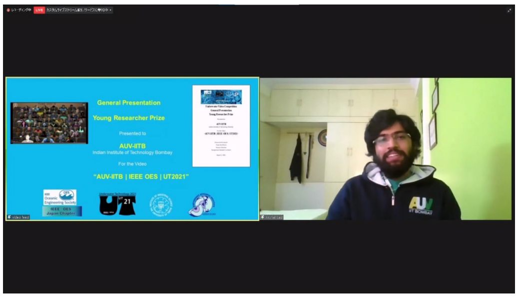


Figure 10: Team AUV-IITB presenting BMS research paper at "Oceans Conference & Exposition Chennai'2021"

Team AUV-IITB is the recipient of the prestigious Young Researchers' Prize awarded by IEEE OES (Ocean Engineering Society) at Underwater Technology Competition 2021, organized by the University of Tokyo, Japan. We presented a 15-minute long video highlighting our journey so far, including the development of six underwater vehicles and various research projects the team has undertaken over the years.



Team AUV-IITB presenting at Video competition organised by University of Tokyo, Japan

The research and development of Matsya 6B got featured in Janes - an international level defense-related magazine. AUV-IITB is amongst the first student teams from India to be recognized at this level.

Team AUV-IITB participated in the Engineer's Conclave as a part of the contingent of IIT Bombay at the inter-IIT Tech Meet 2021 held virtually. The team presented a poster demonstrating the working methodology and capabilities of Matsya. The event helped in increasing the team's outreach amongst like-minded tech enthusiasts coming from various IITs. The progress made by the team was acknowledged and appreciated by all the participants.

Last year, the team participated in the Tech Expo event of Abhiyantriki 2020, the Annual Technical Festival of KJ Somaiya College of Engineering, Mumbai. The team presented the history of Matsya from 2011 to 2020 to a large number of technocrats, enthusiasts, and students. This expo had exhibits from major organizations like DRDO, BARC, IMD, and DAE.

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 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.

Team AUV-IITB was invited to present a research paper for the prestigious International Conference INEST India 2020, INS Shivaji, Lonavala before the Chief of Navy and International marine specialists. Unfortunately, the event was called off due to Covid-realted circumstances.

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 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.