Technical Design Report of Matsya 5B and Matsya 4C, Autonomous Underwater Vehicles

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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 servo controlled manipulator, machine learning for vision and inter vehicle communication.**

I. Introduction

Matsya 5B and Matsya 4C are the two AUV(s) developed this year by a multidisciplinary student-faculty group at IIT Bombay to facilitate research and development in underwater robotics as well as to participate in the International RoboSub Competition. With the integration of a robust manipulator and an improved autonomous decision-making system, this year's vehicles are capable of performing all the tasks and addressing various challenges defined by the competition.

AUV-IITB is a group of around 40 students from different specializations having a strong motivation to explore the field of Underwater Robotics. It consists of four sub-divisions, namely Mechanical, Electronics, Software and Business. Matsya 5 has seen three years long development and testing cycle with the majority of mechanical components, software stack and electronics boards designed in-house by the team members. Matsya 4, which was retired in 2017, has been brought back to being operational in a duration of just six months.

Fig. 1: Matsya 4C and Matsya 5B

II. Competition Strategy

The objectives and challenges at RoboSub 2019, added an extra layer of complexity to the tasks last year, through challenging environment manipulation. The team approached the competition with a major focus on error-minimized reproducibility of the existing design and increased reliability of Matsya's performance in tasks at RoboSub. To start with, structural changes were made to previous iteration of Matsya to give front manipulator's position feedback through an increased field of view of the front camera. Last year, because of the inter-related nature of the tasks, we had numerous environment and mapping related parameters to be tuned just before the run. Modifying them was error prone and time consuming, hence a major re-structuring was done in the software architecture this year. This was done by incorporating abstractions in parameters in the architecture itself and also have different sanity checks and data validation scripts.

At RoboSub '19, we are planning to deploy two vehicles, Matsya 5B and Matsya 4C. Matsya 5 will head for the 'Drop Garlic' after going through the gate, while Matsya 4 would focus on completing initial tasks, the gate and then the two buoys. This way the better equipped Matsya 5 would get more time on manipulation tasks while Matsya 4 attempts the gate and buoys. Matsya 4 after attempting the single buoy, would move on to face the claimed side of the three sided buoy and touch it. In 'Drop Garlic', both markers will be dropped in the closed section, instead of the open section with the help of the marker dropper. We plan to collect the garlic from the gate using our front manipulator and drop them at the open side of 'Drop Garlic'. We will go for the random pinger for Matsya 5 to attempt 'Stake through Heart' and 'Expose to Sunlight' tasks.

III. Vehicle Design

The development, design and research works of the team was focused mainly on improvements in avenues leading to more capable and reliable systems. We concentrated both on making the current system robust like space optimization, improved sub-systems and at the same time explored new technologies like machine learning, under water communication. Sufficient time was spent in testing and optimizing each of the modules in all the sub-divisions.

Machine Learning for vision

Visual feed is very susceptible to lighting conditions, depth, colors in the object, hence making it extremely difficult to use only standard image processing tools like color detection, morphological operations and get results for tasks with complex designs. This year we have tried to use Machine Learning based approaches for object detection to make our system robust against varying conditions. We tried YOLO[1] v2 and v3 and different CNN network designs which could perform fast enough on real time image feed. For most tasks the accuracies are good and in complex tasks the performance is better than our previous approach.

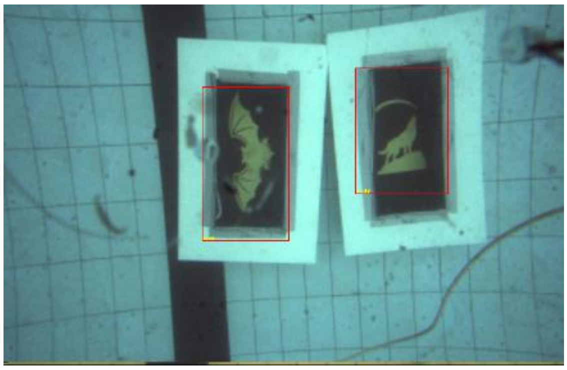

Fig. 2: wolf and bat detection from vision

Underwater Communication

As we are competing with two vehicles at RoboSub and have constraint of single DVL, simultaneous localization could only be achieved by underwater communication. For in-air testing and designing of the protocols, we built our own transmission and receiver system over which we ran a UART communication protocol to establish two vehicle communication. With speaker emitting a certain frequency, mounted on a Matsya 4 without DVL, Matsya 5B with DVL can detect its position by using the time-differences in getting the signal at its four hydrophones (Acoustic localization). The actual position of Matsya 4 will be calculated by Matsya 5 and sent back through a speaker. Matsya 4 using its hydrophone can detect and process it to extract data.

Improved and Reliable Manipulator

This year's Matsya has an improved front manipulator with an end-effector and a human-arm like shoulder-elbow gripping design. Finger like end-effector was introduced this year to tackle the gripper related tasks. Most of those tasks involved gripping an open frame object. Disc coupling was introduced in ”shoulder”

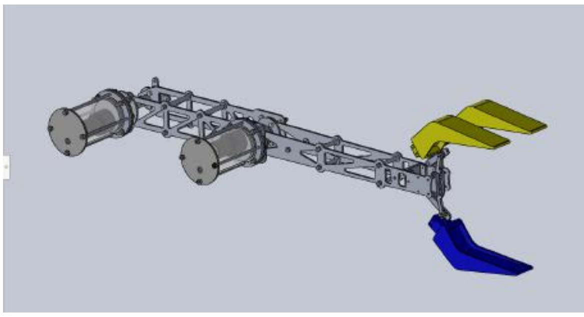

Fig. 3: CAD of Arm on Matsya 5B

joint to eliminate play error while reducing shear stresses in a overall small form factor.

In-house DAQ communication interface

For sampling data form the hydrophones we have a Data Acquisition (DAQ) system, communication with which requires running a Windows node in the virtual environment, as its library supports Windows while all our code runs on a Ubuntu system. Running a Virtual Machine caused unreliability including not being able to establish connection with the VM player or not being able to communicate with DAQ. To solve this we did a reverse engineering to find the working of the library for communication with DAQ and tried to simulate it from Ubuntu itself. We are now able to connect to the DAQ system and able to communicate data, this led to a more reliable system and also giving us a lot more control and a closer look at the communication channel.

Space Optimization and Restructuring

To provide the front camera a better field of view, without altering the length of the vehicle, a new space-optimized DVL hull was designed which occupies 22% lesser volume than the previous hull. The hull body is made from Al-Alloys which provides it a safety factor of >2 at 20m depth while resulting in 35% weight reduction.

Mission planner

The mission planner is the module for dynamically selecting the task. It has to take care of the requirements of tasks, time remaining, distances of tasks and number of attempts per task. So deciding when to do what requires lot of information processing and conditions to check, requiring lot of data and parameter values to be fed by us, thus leading to more chances of manual errors. Hence this time the design is based on providing layers of abstractions, such that the parameters that are specific to tasks are in the inner layer and would be tuned during the testing and can be then left untouched and only the information which are run specific is exposed in the outer layer. This helped in building a more modular structure thus making writing tasks more easier and less error prone.

Compact Elec Stack

With space constraints due to GPU and ESCs’ mounting on the hull, Elec stack is designed to fit in half the place as compared to last year. The backplane based modular system provides an interface for electronic boards to be plugged in directly, thus avoiding a huge amount of wiring. The communication platform used is on-board Controller Area Network (CAN). The system faces a huge hoard of messages sent by the various node to each other and it is what makes the vehicle a very interconnected one. Safety features such as reverse battery voltage protection, over-current protection, soft kill for thrusters are also added.

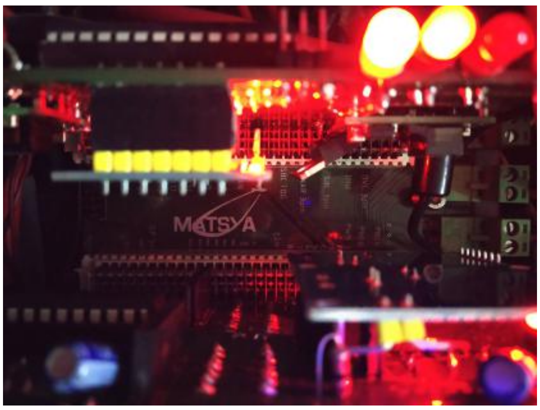

Fig. 4: Elec stack in Matsya

IV. Experimental results

Tests on Simulator

Some logical errors in the code gets removed by test benches but for testing different heuristics it becomes essential to have an arena like setup where complete code for the Matsya can be tested and analyzed.

- Controls: The six DOF PID controller was tuned in the simulator by a novel autotuning algorithm designed using the genetic algorithm. The control error in orientation was less than a half a degree and in position, it was less than a centimeter.
- Sensors and noise: The data from the physics model is intentionally shifted and modified to simulate the offsets in placement of the sensors like DVL, Pressure Sensor and IMU and also synthetic noise is added in order to test the robustness of our algorithms. For vision, the background near the tasks was changed to images from transdec for testing object detection.
- Tasks: Models of this year's tasks were made using Gazebo's model editor. Texture mapping was done on the parts of a task to simulate the visual aspect. Multiple tasks were arranged to get an approximation to the RoboSub arena, using which the code is tested before pool testing.

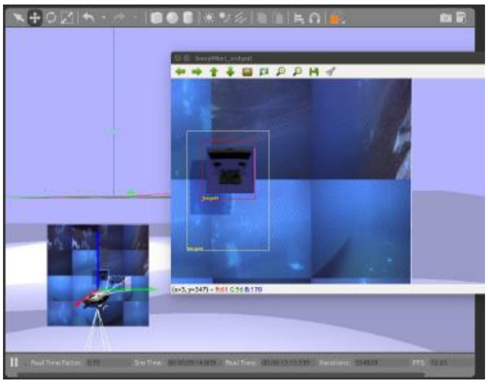

Fig. 5: Gazebo model for Jiangshi

Pool testing of tasks

Initially, videos were taken of each task under different environmental conditions for training and testing the neural networks, and then the overall tasks were tested.

1) Qualification task: This task was tested in two parts: gate and the pole. Gate detection and passing through it, pole detection and taking U-turn around it, and finally both integrated together for the complete task.
2) Enter the Undead Realm: This task is similar to the qualification task and was completed in a short span of time. We focused on moving through the 40% section.
3) Slay Vampires: We tested the state machine to attempt the single buoy and then the three sided one from all the three sides.
4) Drop Garlic: First we tested the detection and centering over both bins collectively. Then tested the simpler part of dropping markers in the open side. After testing on detection and aligning for actuating the lever, we plan to move the lever and eventually to drop both markers in the initially closed side.
5) Stake through Heart: We perfected searching and centering before the task using the complete board for detection, then we tested centering and torpedo shooting through the heart shaped hole, and then trained the model to identify the open and closed ovals. After testing shooting through the open hole, we worked on improving the lever actuation to open the initially closed oval.

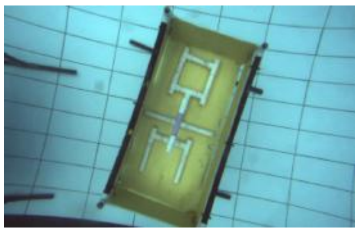

Fig. 6: Props for coffin and Dracula

6) Pinger and arm manipulation: The pinger localization was tested and improved to center over pinger such that the nearby props are visible to the bottom camera when the pinger tasks gets completed. We tested gripping of all the manipulation tasks with the gripper.

Testing of different sub-systems

- Machine Learning for vision: To choose the best model and tune the hyper-paramters, we started training YOLO on dataset of previous years' tasks. We needed a model which could be trained with dataset containing images mostly from our pool and should be able to work in the RoboSub arena. We tested on YOLO version 2 and version 3, since the accuracies gained was similar when trained sufficiently. We decided on using YOLO v2 since it is a smaller network and requires less GPU memory which is compatible with our on-board GPU, Nivida GTX 1660.
- Underwater Communication: We initiated our testing with in-air setup with 30W air-speaker and microphone. Communication was achieved with FSK modulation using two frequencies differing by 5khz. At the receiver end, the signal is amplified and demodulated to get the data. We used UART communication protocol for data transmission, as it is similar and have small package size. We were able to send and receive data with the speed of 300baud/sec in air.
- In-air Waterproofing: To ensure waterproofing of pressure hulls and detect leakage points, we devised a mechanism by using pressure sensor, vacuum pump and a safety valve. The hulls are vacuumed to create actual pressure conditions and then pressure readings, taken from the valve, are plotted. The time constant of the curve was found to be proportional to the diameter of the possible leakage point and hence appropriate action can be taken after initial observations. This mechanism helps us to find leaks that might have come up with time and can save the electronics and sensors from getting damaged.
- Depth Analysis of DVL Hull using ANSYS: We have ensured the strength of the pressure hull 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.

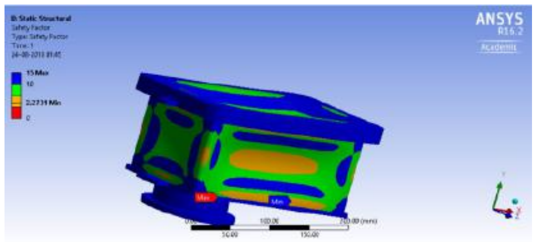

Fig. 7: ANSYS of DVL Hull at 20m depth

V. Acknowledgements

We would like to thank the Industrial Research and Consultancy Centre of IIT Bombay and the National Institute of Ocean Technology Chennai for continuous administrative and monetary support during the project and for hepling us participate in RoboSub 2019. The support of the Dean R&D's office was essentially crucial in the successful execution of the project. We would also like to thank Prof. PSV Nataraj from System and Control Department IIT Bombay, for issuing us a GPU on which we could train our Machine Learning Models. Big thanks to RoboNation as well for gifting us Nvidia Jetson TX2, with which we were able to revive Matsya 4.

We sincerely appreciate the generous support from our sponsors. They played an instrumental role in helping us meet our goals within our budget constraints. Special thanks to our vendors Blue Robotics and Teledyne RDI for their support in case of technical problems.

References

[1] Joseph Redmon, Santosh Divvala, Ross Girshick, Ali Farhadi, *You Only Look Once: Unified, Real-Time Object Detection* 2015.

[2] Welch, Greg and Bishop, Gary, *An Introduction to the Kalman Filter.* 1995.

[3] Ashok Kumar Tellakula, *Acoustic Source Localization Using Time Delay Estimation.* 2007.

Appendix A: Expectations

Subjective Measures			
	Maximum Points	Expected Points	Points Scored
Utility of team website	50	45	
Technical Merit (from journal paper)	150	150	
Written Style (from journal paper)	50	45	
Capability for Autonomous Behavior (static judging)	100	90	
Creativity in System Design (static judging)	100	90	
Team Uniform (static judging)	10	9	
Team Video	50	45	
Pre-Qualification Video	100	100	
Discretionary points static (static judging)	40	35	
Total	650	609	
Performance Measures			
	Maximum Points		
Weight Matsya 4C	acc. Table 1/ Vehicle	35	
Weight Matsya 5B	acc. Table 1/ Vehicle	-140	
Marker/Torpedo over weight or size by $<$ 10%	minus 500 / marker	0	
Gate: Pass through	100	100	
Gate: Maintain fixed heading	150	150	
Gate: Coin Flip	300	300	
Gate: Pass through 60% section	200	0	
Gate: Pass through 40% section	400	400	
Gate: Style	+100(8x max)	720	
Collect Pickup: Crucifix, Garlic	400 / object	400	
Follow the ”Path” (2 total)	100 / segment	200	
Slay Vampires: Any, Called	300, 600	900	
Drop Garlic: Open, Closed	700, 1000 / marker (2 + pickup)	2100	
Drop Garlic: Move Arm	400	0	
Stake through Hearth: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	2200	
Stake through Heart: Move lever	400	400	
Stake through Heart: Bonus - Cover Oval, Sm Heart	500	500	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with object	400 / object	400	
Expose to Sunlight: Open coffin	400	200	
Expose to Sunlight: Drop Pickup	200/ object (Crucifix only)	0	
Random Pinger first task	500	500	
Random Pinger second task	1500	1500	
Inter-vehicle Communication	1000	300	
Finish the mission with T minutes(whole + fractional)	Tx100	200	

Appendix B1: Component Specifications Matsya 4C

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control		Buoyancy Stubs	-	
Frame		Delrin and Aluminium frame	Designed in-house	-
Waterproof Housing		Aluminium Hulls (6 hulls)	Depth rating: 150ft	-
Waterproof Connector		Aluminium connectors	Designed in-house	100-150USD
Thruster	Seabotix	BTD150	2.9 kgf	-
Motor Control	Dimension Engineering LLC	Syren-10	Voltage based DC motor speed controller	50 USD
High Level Control	Microchip Technology	Atmega 328p	Low-power CMOS 8-bit RISC microcontroller capable of achieving speed upto 1MIPS per Mhz	15 USD
Actuators	Janatics	A51012025O	Stroke Length:25 mm	30 USD
Propellers	-	-	-	-
Battery	Tattu	LiPo Battery	4 Cell and 10000 mAh x 2	300USD
Converter	Texas Instruments	PTN 78060	3A Wide Input Output Adjustable Switching regulator	20 USD
Regulator	picoPSU	160-XR	160W 12V input DC-DC ATX power suppy	40 USD
CPU and GPU	Nvidia	Jetson TX2	128-bit ARM processor, 8GB GPU, 256 cuda cores	-
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	Gx3	-	-
Doppler Velocity Log(DVL)	-	-	-	-
Camera(s)	Logitech	Logitech c270	720p/30fps	60 USD
Hydrophones	Teledyne	RESON Underwater TC Hydrophones	-	-
Manipulator	-	-	-	-
Algorithms: vision	OpenCV, YOLO	Task position estimation	Colour and shape detection, Object detection from by YOLO, parallel and sequential processing, lens formula	-
Algorithms: acoustics	FFTW	Time difference of arrival	Filtering in frequency domain, and time domain	-
Algorithms: localization and mapping	Orocos BFL	Kalman filter	Sensor fusion for localisation and custom mapping	-
Algorithms: autonomy	-	State machine and Planner	Probablistic decision making and mission planner	-
Open Source Software	-	-	-	-
Team Size (number of people)	40	-	-	-
HW/SW expertise ratio	2:1	-	-	-
Testing time: simulation	45-60 hrs	-	3hrs/day, 15-20 days	-
Testing time: in-water	36-45 hrs	-	3hrs/day, 12-15 days	-

Appendix B2: Component Specifications Matsya 5B

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control	-	Buoyancy Stubs	-	-
Frame	-	Aluminium Frame	Designed in-house	750-800 USD
Waterproof Housing	-	Aluminium Hulls (6 hulls)	Can theoretically withstand pressures upto 150ft depth	2000-2200 USD
Waterproof Connector	-	Aluminium connectors	Designed in-house	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	Low-power CMOS 8-bit RISC microcontroller capable of achieving speed upto 1MIPS per Mhz	15 USD
Actuators	Janatics	A51012025O	Stroke Length:25 mm	30 USD
Propellers	-	-	-	-
Battery	Tattu	LiPo Battery	4 Cell and 16000 mAh x 2	400 USD
Converter	Texas Instruments	PTN 78060	3A Wide Input output Adjustable Switching regulator	20 USD
Regulator	picoPSU	160-XR	160W 12V input DC-DC ATX power suppy	45 USD
CPU	Intel	Intel i7		-
GPU	Nvidia	Gaming GeForce GTX 1660	GDDR5, 6GB, 120 Watts	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-234	-	-
Hydrophones	Teledyne	RESON Underwater TC 4013	-	-
Manipulator	-	Developed in-house	2 DOF servo-operated arm, pneumatic-driven end effector	300-350 USD
Algorithms: vision	OpenCV, YOLO	Task position estimation	Colour and shape detection, Object detection from by YOLO, parallel and sequential processing, lens formula	-
Algorithms: acoustics	FFTW	Time difference of arrival	Filtering in frequency domain, and time domain	-
Algorithms: localization and mapping	Orocos BFL	Kalman filter	Sensor fusion for localisation and custom mapping	-
Algorithms: autonomy	-	State machine and Planner	Probablistic decision making and mission planner	-
Open Source Software	-	-	In the near future	-
Team Size (number of people)	40	-	-	-
HW/SW expertise ratio	2:1	-	-	-
Testing time: simulation	60-90 hrs	-	3hrs/day, 20-30 days	-
Testing time: in-water	450-550 hrs	-	9-10 hrs/day, 50-55 days	-

Appendix C: 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.

School children at our lab

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

The Team last year participated in the Tech-Connect event of TechFest, Asia's Largest Technical Festival, organized by IIT Bombay. Also, the team itself held many workshops in the campus, open for all, to have thought-provoking discussions with the students and professors about the design strategy and the general working concept of the AUV. This not only helps the team get fresh ideas, but it also helps us ponder on a few details which the team might have missed. The team presented Matsya in the 4th World Congress on Disaster Management conducted at IIT Bombay. This gave us an industrial exposure towards the need and applications of AUVs and ROVs during disaster management and about various challenges in deploying in the water bodies. This not only helped us in understanding the importance of the work we do more deeply but also sparked thoughts into finding solutions to various challenges in using AUVs in uncontrolled environments such as dams, lakes, oceans.

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.

Matsya 5 at World Congress on Disaster Management 2019

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.