Technical Design Report of Matsya 5A, Autonomous Underwater Vehicle

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***Abstract*—Matsya, which means 'fish' in Sanskrit, 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 the servo based manipulator arm, the battery merging system, six actively controlled degrees of freedom, and the dynamic mission planner.**

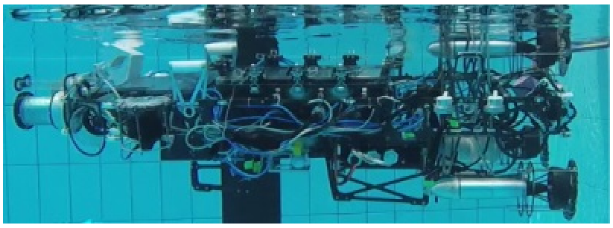

Fig. 1: Matsya 5A in testing

I. Introduction

Matsya 5A is an AUV developed 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 vehicle is capable of performing all the tasks and addressing various challenges defined by the competition.

AUV-IITB is a group of 26 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 Public Relations. Matsya 5A has seen a year-long development cycle with the majority of mechanical components, software stack and electronics boards designed in-house by the team members.

II. Competition Strategy

As this year's tasks are much different than those of previous years, and since most require some sort of manipulation, we had to make some fundamental changes in all the sub-divisions. Tasks like the roulette require the color to be same as the one on the gate through which the vehicle entered. This forced a change in the mission planner module of the software stack, which previously did not handle such interdependence of tasks, and treated each task as a separate one. Tasks such as the torpedo, the coin collection, the bins near pinger and the funnels all require manipulation either in front, bottom or top.

Taking into account the time and resources that we had throughout the year, and our need to spend our last few weeks on testing this vast variety of tasks, we arrived at the conclusion that to tackle this, we would need a single arm with two degrees of freedom, which would be able to go in all the three directions: front, bottom, and top. To be able to move the arm anywhere within a plane, we chose to have a continuous actuation for the joints of the arm. The end-effector was designed keeping in mind the fact that we needed to capture both golf balls and the torpedo handle. The development of this multi-functional arm called for significant thought into the design and with proportionate input from the design team, we could achieve this without consuming significant testing time.

Considering the tasks of this years

RoboSub, our strategy is as follows: The color of the gate is stored for later use in roulette. In the Dice task, the numbers are detected through vision and the overlap of different dice in the image, is avoided through the task state machine. Mission planner then maximizes the score by choosing the correct dice. The gold coin is collected by pushing the plate and collecting it either directly through the arm, or by picking it up from the tray. The collected gold coin is then dropped either in the roulette or the funnel, by lowering and raising the arm respectively. Similarly, the red and green golf balls are collected by detecting them and picking them up by the arm and then raising the arm above the funnel to drop it. The arm uses motors which provide enough torque to operate it in the air as well. This enables us to drop the coins in the funnel even when we are surfaced up inside the square.

III. Design Creativity

Arm

This year's problem statement requires one to attempt tasks in multiple directions. With gripping task at the bottom, coin collection and jackpot machine in the front and cashing coins above the surface of the water, we were clear that attempting these tasks with a simple binary pneumatic actuators would take up a prodigious amount of resources, and yet would not give us enough flexibility. We wanted to at least give enough hardware to attempt all tasks. Our requirement of using as little space and resources as possible lead us to the idea of designing a 2 DOF arm for the vehicle which could attain all points in a single plane. We have used two servo motors and a pneumatic piston to operate the arm. The control circuitry for the servo motors has been developed in-house from scratch.

Dynamic Waterproofing

Working with servo motors in water presented the next hurdle: sealing. We knew how to waterproof systems which were static but now need was to do this dynamically.

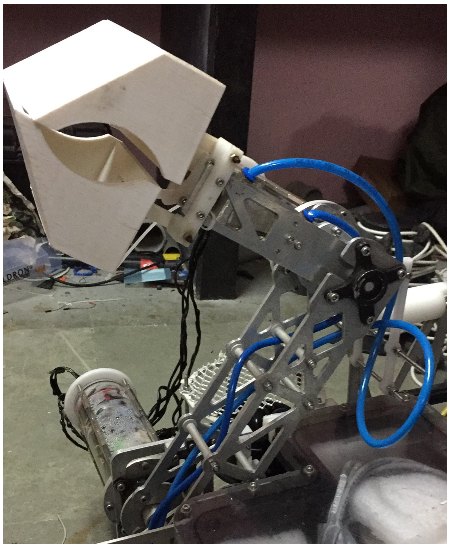

Fig. 2: Arm on Matsya 5A

Waterproof servos meeting our large torque requirement available in the market were either expensive or bulky. So we decided to implement a dynamic waterproofing method ourselves. After several experiments and iterations, we developed an o-ring based seal which could waterproof a regular servo motor.

Thruster Configuration

Since our current vehicle is slightly heavier than our previous one, we decided to increase the number of thrusters from 6 to 8 to gain speed. Placing 8 thrusters about the center of mass such that static, as well as dynamic stability, is achieved was a challenging task. Three surge thrusters were placed at the vertices of an equilateral triangle to distribute the thrust safely along the sides and finally to the frame.

Dynamic Mission Planning

Taking into account the mistakes that cost us last year, we have introduced a novel mission planner that is capable of switching tasks in between based on the feedback from vision. This has also been done to reduce the dependence on the mapping of tasks in the arena.

Probabilistic State Machine

In order to improve the stability and consistency in performing a task, we have shifted to a probabilistic model, where the decisions in the State Machine are made based on the probability of pose detection from vision. This has been done keeping in mind that the best form of planning cannot be deterministic, and that this is the first step in that direction.

Multi-Task Detection in Vision

To facilitate dynamic mission planning, our vision package was modified to detect multiple tasks simultaneously, as opposed to last year wherein only a single task detection was possible at a time. Also, to get the probability of task pose estimation from vision, a Kalman filter[1] was used on its output. As we look to move towards deep learning based approaches, this will be combined with the probability of detection in order to further enhance it.

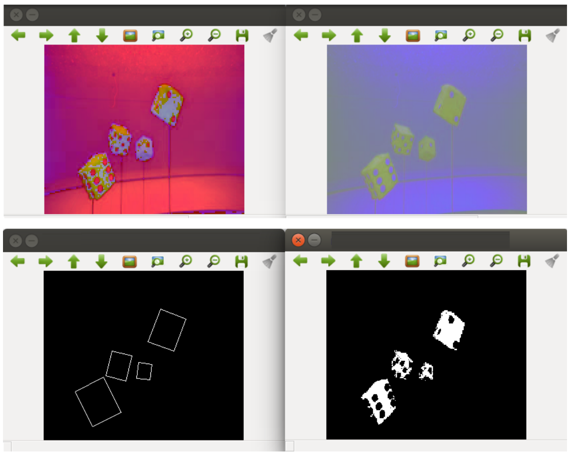

Fig. 3: Dice Task Processing

Acoustic Localization

This package takes data from the Data Acquisition (DAQ) system, processes the signal, and tries to localize the underwater sound source, using the concept of difference in time of arrival (TOA) [2]. The data from the hydrophones is first received by the DAQ and then sent to the computer of the vehicle. Since the driver for the DAQ which we were using, was available only on Windows platform, we had to use a virtual machine in order to get the data. The communication between the vehicle's Linux OS and the virtual machine was done through socket programming.

Controller and Navigator

We are using a PID controller for each degree of freedom. The orientation is controlled over quaternions, in order to overcome the problem of gimbal lock which arises while using the Euler representation. We have also designed an interface for tuning the PID constants dynamically, to reduce the testing time. The Navigator breaks down set-points and feeds it to the controller in order to minimize the time taken in the transition from one point to another. It has various modes, and is capable of an auto timeout, by estimating the time for transition.

Battery Merging System

Matsya 5A is powered by 2 batteries which power the thrusters, the electronics system, and the onboard SBC. The voltage of each battery is read and the one with the higher charge is used. The reading is taken when the battery is idle, so as to avoid measurement errors due to IR drop. After the batteries discharge to a minimum preset level, the system shuts down the thrusters and alerts the SBC.

Controller Area Network

The current vehicle was designed to be a highly advanced AUV with adaptable system behavior. This required the presence of a communications platform that was scalable, had full system interconnectivity and was easily modifiable. The CAN network on Matsya 5A fulfills these expectations.

Backplane Based Layout

For systems with high connectivity to the external world, such as an AUV, connections coming into the system can cause it to be bulky and messy. The backplane provides an interface for electronic boards to be plugged in directly, thus avoiding a huge amount of wiring.

IV. Experimental results

Tests on Simulator

- Controls: The six DOF PID controller was tuned in the simulator by a novel

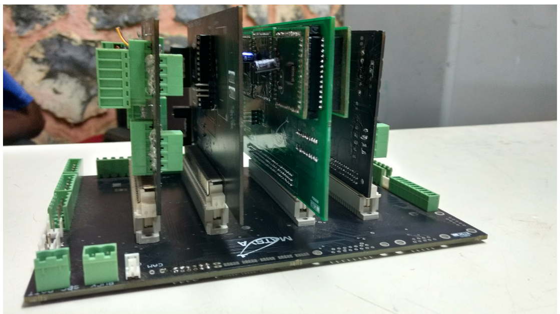

Fig. 4: Backplane with boards

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.
- Manipulator: First, the arm model was attached to the model of Matsya, and then the joints were actively controlled to simulate the actual motion of the arm. The end effector was also controlled by modeling the piston actuation.
- Tasks: The models of this year's tasks were made in SolidWorks and then imported to our simulator in Gazebo. Texture mapping was done on the parts of a task using Blender to simulate the visual aspect. Multiple tasks were arranged to get an approximation to the RoboSub arena, using which the State Machine and Mission Planner are tested before the pool testing.

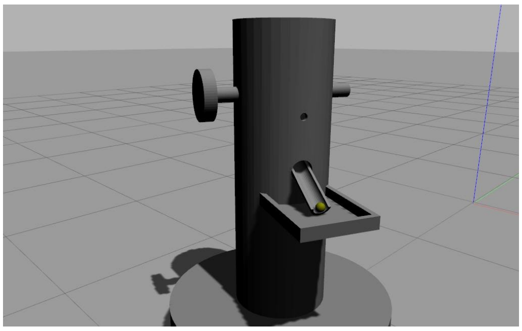

Fig. 5: Gazebo model of the Coin Collection Task

In-water testing before tasks

- Corrections for CG and CB: The small errors in the position of the center of gravity and the center of buoyancy from that in CAD, was noted by giving equal PWM to the set of thrusters for a DOF and noting the error in other DOFs.
- Controls and Navigation: Each DOF is tuned individually first and then all six are tuned together to minimize the rise time, the settling time and the oscillations. Various plans of the navigator are tested including the auto plan mode.

Pool testing of tasks

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

1) Qualification task: This task was attempted in two parts: the gate and the pole. Gate detection and passing through it, pole detection and taking u-turn around it, and finally both parts integrated together for the complete task.
2) Enter Casino: This task is similar to the qualification task and was completed in a short span of time.
3) Play Slots: This task was attempted by first finding the center of the slot machine, and subsequently the relative position of the handle and the slots. Preference was given to shoot torpedoes through the always open red slot. This was due to the time constraints while testing and also during the semi-final run.
4) Dice: The approach was to locate the direction in which there is no overlap between the dice, and then detect the individual dice and then touch them such that points are maximized.
5) Roulette: The approach was to first locate and center on the overall roulette and then go down and center on the colored sections. Since the Roulette is rotating, we had two approaches: one to rotate the vehicle at the same rate as roulette and then center on the color and other to directly center by just translating. Since the rotation speed was much less than the vehicle's speed,

we chose the latter after testing both the approaches.

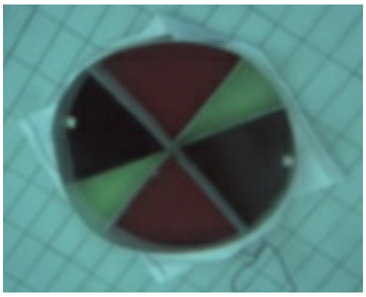

Fig. 6: Roulette Task Testing

6) Cash in your Chips: The idea is to collect the red and green golf balls from the bins, after localizing on the pinger, with the help of the arm. The vehicle would then rise and center on the lower portion of the funnel until it is close by and then the ball would be dropped from the arm in a raised position.

Testing of different sub-systems

- Auto Frequency detection: For testing the accuracy of noise removal by our acoustic filtering algorithm, we used the Fast Fourier Transform to estimate the frequency of the sound source. It was then compared against the ground truth of the frequency of the source. The results were found to be accurate to 10Hz error.
- Communication Stack Testing: The communication platform used onboard Matsya 5A is a 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. Regular functionality tests and Stress tests are done to ensure that the system is fully functional. The data rate of the CAN network on a normal testing is around 150-200 bytes per second (bps).
- Thruster Profiling: Thruster profiling is done to map the PWM input to the thrust generated. This mapping is then used by the controller for improved performance. As a result, the accuracy of the thruster is a parameter that we test to ensure that it gives us the desired results.
- Dynamic Waterproofing: As servo motors were used in our manipulator this year, we needed its shaft to be dynamically waterproof when in operation. A new seal was developed and tested to check its feasibility. Test results were used to check and determine the following: waterproofing under no load state of the shaft, waterproofing under loaded state of the shaft and torque required to overcome friction in the seal.

V. Acknowledgements

We would like to thank the Industrial Research and Consultancy Centre of IIT Bombay for continuous administrative and monetary support during the project. 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 the Industrial Design Center IIT Bombay for their support in the development of the manipulator.

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

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

Appendix A: Component Specifications

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 150 ft depth	2000 - 2200 USD
Waterproof Connectors	-	-	Designed in-house	150 USD
Thrusters	Blue Robotics, Videoray	T200 and Pro 4 respectively	5.1 kgf and 9.5 kgf respectively	3000 USD
Motor Control	Blue ESC's	Blue Robotics	-	200 USD
High Level Control	Microchip Technology	Atmega 328p	Low-power CMOS 8-bit RISC microcontroller capable of achieving throughputs upto 1MIPS per MHz	15 USD
Actuators	Janatics	A51012025O	Stroke length: 25 mm	30 USD
Propellers	-	-	-	-
Battery	TATTU	LiPo Battery	4 Cell and 16000mAh	700 USD
Converter	Texas Instruments	PTN 78020	6A Wide Input Adjustable Switching Regulator	50 USD
Regulator	picoPSU	160-XT	160W 12V input DC-DC ATX Power Supply	45 USD
CPU	Intel	Intel i-7		-
Internal Comm Network	Microchip Technology, CANUSB	MCP 2515, MCP 2551, CANUSB	1 Mb/s operating limit	150 USD
External Comm Interface	-	Ethernet	10-100 Mb/s	-
Programming Language 1	C++	-	-	-
Programming Language 2	Python	-	-	-
Compass	-	-	-	
Inertial Measurement Unit (IMU)	Microstrain	Gx5	-	-
Doppler Velocity Log (DVL)	Teledyne	Explorer DVL	-	-
Camera(s)	Allied Vision	Mako G	-	-
Hydrophones	Teledyne	RESON Underwater TC Hydrophones	-	-
Manipulator	-	Developed in-house	2 DOF servo-operated arm, pneumatic-driven end effector	300 - 350 USD
Algorithms: vision	OpenCV	Task position estimation	Colour and Shape detection, 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 localization, and custom mapping	-
Algorithms: autonomy	-	State Machine and Planner	Probabilistic decision making, and mission planner	-
Open source software	-	-	In the near future	-
Team size (number of people)	26	-	-	-
HW/SW expertise ratio	2:1	-	-	-
Testing time: simulation	60-90 hrs	-	3hrs/day, 20-30 days	-
Testing time: in-water	540-650 hrs	-	9-10hrs/day, 60-65 days	-

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.

Dean of Student Affairs with Matsya 5A at Tech-Connect, TechFest 2017

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.

School children at our lab

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 4 at Tech and RnD Expo 2017

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, 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.