Research and Development of Matsya 4A, Autonomous Underwater Vehicle

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Abstract— Matsya, stands for a fish in Sanskrit, is a series of Autonomous Underwater Vehicles (AUVs) being developed at Indian Institute of Technology(IIT) Bombay with the aim of delivering a research platform in the field of underwater robotics and to promote autonomous systems. AUV-IITB is a forum for students and faculty to pursue their interests in underwater robotics. AUV-IITB team has developed four vehicles each one more advanced as well as more capable than it's predecessor. Major architectural changes have been made to the subsystems by designing them from the perspective to handle tasks in real time. Although, the latest vehicle, Matsya 4A has its design philosophy similar to Matsya 3.0, it has majorly improved upon the previous versions in terms of weight optimization, reliability, endurance, speed, aesthetics and cognition.

1 Introduction

Matsya 4A 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 integration of a robust Acoustic Localization System and improved control system, this year's vehicle is capable of performing majority of the tasks and addressing the challenges defined by the competition.

AUV-IITB is a group of 25 students from different specializations having a strong motivation to explore the field of Underwater Robotics. It has three divisions namely Mechanical, Electronics, and Software. Matsya 4A has seen a year-long development cycle with majority of components, underwater connectors, software stack and electronics boards designed in-house by the team members.

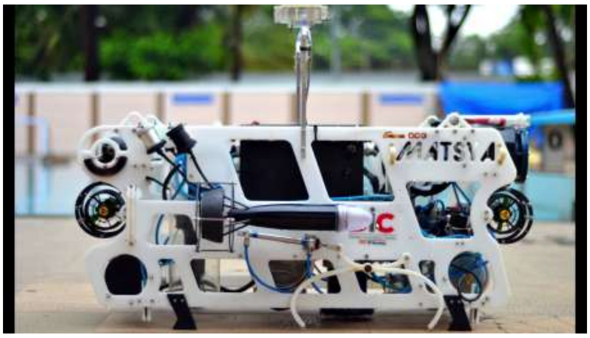


Figure 1: *Matsya 4A*

2 Mechanical

Matsya's mechanical subsystem consists of three specialized sub-divisions namely: actuators, frame and hull. Every sub-division undergoes predefined design flow (Figure 2) to deliver reliable and optimized components.

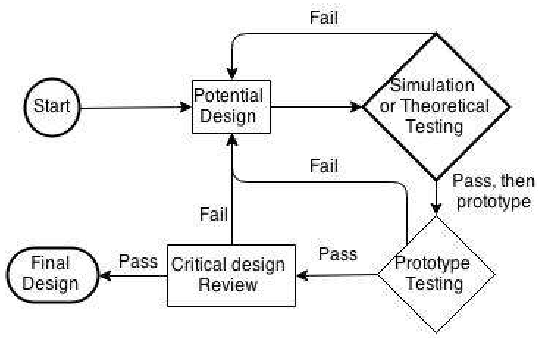


Figure 2: *Design Flow*

2.1 Hull

Hull is a pressure chamber meant to provide a waterproof enclosure to place electronics and other water sensitive components of Matsya.

To incorporate various needs like accessibility to inner component(s), field of sensing etc., Matsya houses four types of hulls namely: battery hull, camera hull, main hull and sensor hull. The hull sub-division also designs custom made connectors, penetrators and underwater switches.

Battery Hull This year Matsya has two battery hulls (Figure 4(a)) of same design. The design objectives for the battery hull include ease of opening & closing while ensuring robust waterproofing. The hull is designed to allow bare hand operation and have a life of 600 cycles of opening & closing.

Camera Hull Because of modular design philosophy, Matsya 4A reuses same hull for camera as Matsya 3.0 (Figure 3(a)). Accurate mounting and enough field of view for cameras are some of the primary objectives that the hull must meet. Similar to battery hulls, the camera hulls are also designed to allow waterproofing operation and opening and closing to be as intuitive as handling a water-bottle.

Sensor Hull Doppler Velocity Log (DVL) hull and Inertial Measurement Unit (IMU) hull fall under this category. For early detection of water leaks, these hulls have been chosen to allow maximum visual from their inner parts. Accurate mounting and electromagnetic shielding are some of the other important design aspects.

Main Hull As the name suggests, the main hull houses almost all the electronics of Matsya. It is not only an amalgamation of all the above design objectives but also includes features like layered electronic stacking and good heat dissipation qualities. The main hull comprises of four parts: base-plate, lateral walls, flange (Figure 3(c)) and end-cap (Figure 3(b)). To reduce cost, side walls are bent from a sheet of aluminum to form two C-shaped structures which are then welded together and thus are made up of more ductile aluminum alloy. The base-plate is made up of a more rigid aluminum alloy since the main hull also provides structural strength to Matsya. The flange is designed to avoid accumulation of water on the top surface and to ensure that no water seeps inside during disassembly. An acrylic end-cap at the top provides a transparent interface for visual detection of water seepage as well as electronic displays and indicators. For ensuring rugged waterproofing, the hull has undergone vacuum impregnation - an industrial porosity sealing technique.

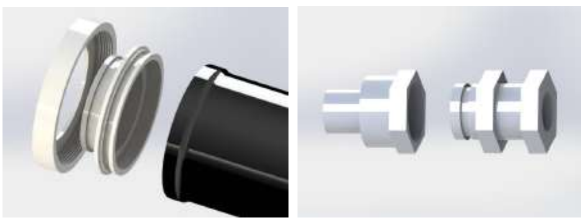
(a) *Camera hull & assembly*

(b) *End cap*

(c) *Flange*

Figure 3

Connectors The team has fabricated in-house dry mateable six pin underwater connectors (Figure 4(b)) to route connections among hulls, thrusters and sensors. The plug and play nature of these connectors makes it convenient to integrate additional components in Matsya and eases the phase of disassembly and replacement. The manufacturing cost for these connectors is around $5 which is nearly twenty times cheaper as compared to the alternative option available in market.



(a) **(b)**

Figure 4: *(a)Design of End Cap for Battery Pod; (b)Connectors*

Penetrators Penetrators are designed to route cables out of hulls for direct connection to the sensors for which simple plug and play connectors cannot be used as they cause data loss and impedance matching problems.

Underwater Switches This year's Matsya has four switches of same design. The design objective for these switches include reliability and good diver interface.

Latches For sealing main hull, pull action toggle latches are fixed on top of the end cap to squeeze the O-ring sandwiched between end cap and flange of main hull. They also incorporate a custom designed lock to prevent accidental opening.

2.2 Frame

Frame is responsible for providing a rigid structure to Matsya's peripherals. The positioning and mounting of peripherals have been done strategically to develop a bottom-heavy open-frame structure which exhibits symmetry, modularity and stability. Benefits of an open frame structure includes easy & fast accessibility and inspection of any component of Matsya. To make the vehicle dynamically stable, the peripherals are placed so as to align the Center of Buoyancy (COB) and the Center of Mass (COM) vertically, with COM lying below COB.

Modularity is one of the most important aspects of Matsya's frame. Every peripheral has been housed inside a hull and the hull is mounted onto a sub-assembly which is then mounted with the rest of the frame in such a way that the peripheral can be replaced or changed without affecting other parts of Matsya. This year, the optimizing process has been divided into two parts: unit optimization and integrated optimization. Both kind of optimization have been done using Solid Structural on ANSYS workbench. In unit optimization, only the sub-assembly is optimized on the basis of weight, strength, impact resistance, and space. While in the integrated optimization, entire assembly of Matsya is optimized on similar grounds as that for unit optimization. One of the key features of integrated optimization is that it distributes load of components and stress on frame in a uniform manner.

Figure 5: *SolidWorks rendering of CAD model of Matsya*

Thruster Positioning Matsya in total has six thrusters: four Seabotix BTD150 and two VideoRay brushed thrusters. Since the VideoRay thrusters are rated for significantly higher voltages, they are operated at 30V and are chosen for surge direction in order to provide higher surge speed. Since the heading angle is controlled by sway thrusters, their separation has been kept as high as possible in order to decrease the thrust for maintaining balancing moment. This particular arrangement allows to cut down power requirement and increase the endurance. As a side effect, this arrangement forces heave thrusters to get close to the main hull. Also the fore thruster is more crowded than that of the aft thruster resulting in production of different thrusts. In order to equalize those, ducts are placed around the thrusters to create similar environments.

2.3 Actuators

This sub-division handles grippers, torpedo launchers and marker droppers of Matsya. All the three actuators are connected to a centralized pneumatic system which uses a standard paintball CO_2 tank as the power source. To control the power, Matsya incorporates six control valves and a pressure regulator to step down the tank's pressure in order to produce a steady output of 100 psi.

Gripper Matsya has two grippers, one on each side of the frame. They have been designed in such a way that they require less ground clearance but when actuated, provide large gripping area. To achieve this, Genetic Algorithm has been used as an optimization tool.

(a) *Normal position* (b) *Actuated position*

Figure 6

Torpedo There are two torpedo launchers mounted on either side of Matsya. The torpedoes are designed to have twisted fins which provide gyroscopic stability. These fins are optimized using ANSYS Fluent and allow torpedoes to travel 2 meters in a straight line with deviation of less than 2 centimeters.

Marker Dropper Like torpedo launchers, there are two marker droppers on each side of Matsya. Though the design of markers is similar to that of the torpedoes, they are bottom heavy which provide them orientational stability. They also incorporate twisted fins which are optimized using ANSYS Fluent. Current version of marker travels 2 meters with deviation of 10 centimeters or less.

3 Electronics

With electronic framework being the core element for interfacing mechanical hardware with software stack, Matsya's electronics has been designed focussing upon the verticals of simplicity, stability and modularity within a distributed architecture (Figure 7). The different subsystems have been integrated through a GPIO Board (Section 3.2) reducing in-air wiring and enhancing the ease of replaceability in case of any failure. A separate daughter processing board has been incorporated in GPIO board to facilitate uninterrupted exchange of information among different subsystems and Single Board Computer (SBC) (Section 3.1). A very subtle emphasis has been given to the power requirements and distribution among the subsystems, thus increasing the endurance manifold.

3.1 Single Board Computer

The core processing unit of Matsya has been upgraded in order to suffice the increased com-

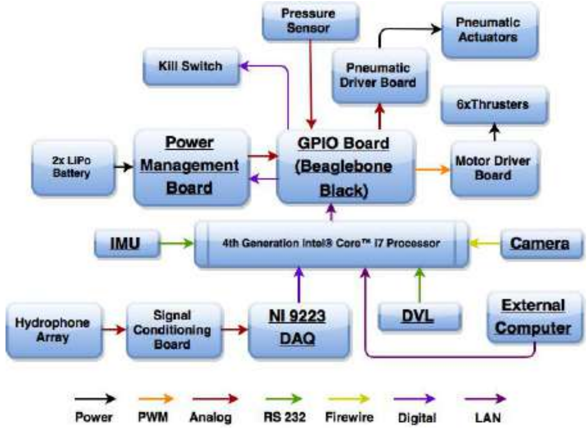


Figure 7: *Electronics System Communication Diagram*

putational requirements due to significant enhancement in the software and acoustic signal processing systems. The current SBC consists of Axiomtek's mini-ITX motherboard (Figure 8) powered by an Intel 4th Generation Core i7 processor running at 2.5GHz along with 8 Gigabytes of RAM.

Figure 8: *MANO882 mini-ITX Motherboard*

3.2 GPIO Board

The General Purpose Input Output (GPIO) Board works as a shield for the BeagleBone Black and provides input and output peripherals to other electronic subsystems. BeagleBone Black is a standalone development board with ARM Cortex-A8 processor running at 1GHz with 512MB RAM. This processor directly communicates with SBC through ethernet. GPIO board has improved the modularity of the system significantly as any new sensors or electronic subsystem can be directly integrated through this board. Moreover, this board also facilitates the required voltage conversion to ensure compatibility of logic levels among all subsystems. It provides digital output peripherals for pneumatic actuators, Pulse Width Modulated (PWM) output signals for motor drivers, input peripherals for underwater switches, battery voltage sensor and pressure sensor. An array of RGB LED is also provided to check status of Matsya and to debug the electronic system. As per the set-points provided by the SBC, the GPIO board executes closed-loop control algorithms providing the desired PWM outputs to individual thrusters.

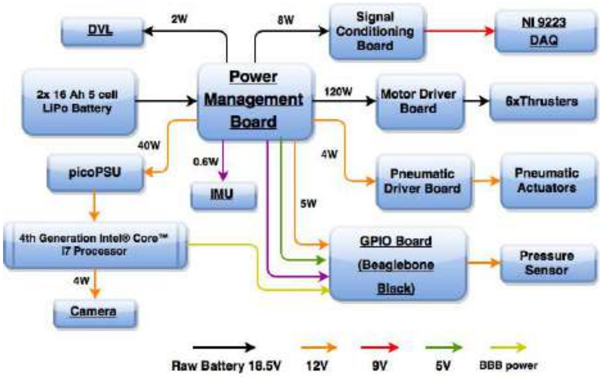


Figure 9: *Power Distribution Diagram*

3.3 Power Management System

Power Board performs task of regulating power among all the sub-systems while incorporating various other features like short circuit protection, reverse battery polarity protection with voltage measurement. Standard voltages 3.3V, 5V and 12V are accessible from a power rail ensuring that the voltage requirements for most of the standard industrial sensors have been satisfied. Power management has its own dedicated microcontroller which performs all the important tasks like battery voltage and current monitoring. In case of low voltage or higher current than expected, it shuts off power of all the vital components.

3.4 Pneumatic Board

The Pneumatic Board provides functionality for the independent operation of the pneumatic actuators without affecting the other subsystems. The board receives commands from the BeagleBone Black for the purpose of firing torpedoes, dropping markers and object manipulation using grippers. There are 6 solenoid valves which can be switched independently using solenoid driver-LMD18400 from Texas Instruments.

3.4.1 Motor Driver Board

The Motor Driver Board integrates all six Siren-10 motor drivers of Dimension Engineering LLC on a single custom designed board and provides ease of replaceability and safety features. With a power rating of over 150W, each of these motor drivers are capable of efficiently driving high-power thrusters. This board can be switched ON/OFF anytime with the help of a heavy duty relay which is controlled by BeagleBone Black.

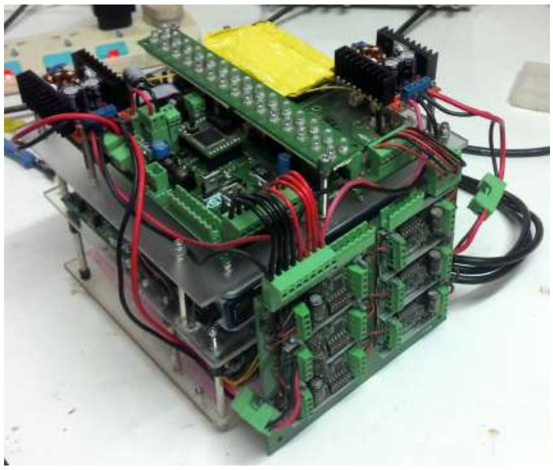


Figure 10: *Electronic Hardware Stack*

3.5 Acoustic Localization System

Acoustic localization unit of Matsya uses four hydrophones to localize with respect to an active sound source. A custom board is designed to condition the signal coming from the hydrophones. This conditioned analog signal is converted to digital signal using DAQ NI 9223 from National Instruments and saved & processed on SBC to estimate the Direction Of Arrival (DOA). The entire system execution is divided into following stages:

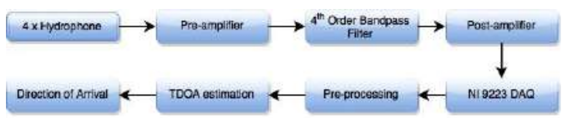


Figure 11: *Acoustic Localization: Five stage process*

- Pre-Amplification: This stage involves pre-amplification of raw hydrophone signals that intrinsically have very low peak to peak voltages. The gain is controlled in order to compensate for voltage compatibility with Analog to Digital Converter (ADC) levels and improve sensitivity.

- Filtering: Elliptic band pass filter is used to remove noise from the amplified signal and passes them to the post amplification unit. Two second order active elliptic filters are cascaded for each hydrophone in order to provide high roll-off factor.

- Post-Amplification: The filtered signal is again passed through a post amplification phase with a fixed gain to make it compatible with the ADC's voltage levels.

- Sampling: Signals from all hydrophones are sampled using NI 9223 data acquisition board. The digital signals are then transferred to SBC through ethernet for further processing and direction of arrival (DOA) estimation.

- Digital Signal Processing: Digital Signals of all hydrophones are processed on SBC to estimate position of pinger relative to the vehicle. After implementing the Fast Fourier and Inverse Transform the signals are then pre-processed to discard noise and to make envelope of the signals uniform. The DOA is finally estimated from the processed signals using hyperbolic positioning [Chan and Ho 1994].

Figure 12: *Custom Designed Acoustic board*

3.5.1 Batteries

Matsya's entire system is powered by two 5-cell 18.5V 16Ah Lithium Polymer batteries. One battery is being used for thrusters & pneumatic actuators while the other one is being used for powering electronic system & the acoustic localization system. With all mission-critical tasks running along with the onboard peripherals, these batteries gives an endurance of about six hours to the vehicle.

3.6 Sensors

Various on board sensors are used to get feedback for control and underwater navigation.

3.6.1 Cameras

Matsya uses two Unibrain Firewire color cameras for its machine vision. The vehicle's bottom view camera is a FireWire-i BCL 1394a board camera while the front view camera is a FireWire-i 1394a board camera. Based on ICX-625 Sony CCD sensor, these cameras provide various features like high resolution color video streaming at adequate frame rates, multi-camera synchronization and real-time control of several camera parameters. Lenses of specific focal lengths are used for front and bottom cameras for getting an appropriate underwater Field Of View (FOV).

3.6.2 Inertial Measurement Unit

For low-drift and precise orientation measurements, Matsya uses 3DM-GX3-25 Attitude Heading Reference System (AHRS) from Lord Microstrain Sensing Systems as its primary navigator. Based on MEMS sensor technology, this device fuses data from its triaxial accelerometer, triaxial gyroscope, triaxial magnetometer and temperature sensors using an on-board processor and provides very accurate inertial measurements. It is directly interfaced to the SBC via RS-232 protocol.

3.6.3 Pressure Sensor

US381 pressure sensor manufactured by Measurement Specialties Inc., is used for the vehicle's depth measurements. With an operating pressure range of 100 PSI, this sensor outputs current in 4-20mA range proportional to the pressure exerted on it's outer diaphragm.

3.6.4 Doppler Velocity Log

Teledyne RDI's Explorer Doppler Velocity Log (DVL) has helped significantly in improvising the navigation and localization framework of Matsya. By fusing data from an onboard inertial sensor and depth sensor, this device provides high precision velocity data useful for real-time underwater navigation using the Doppler effect of sound waves. Rated at depths up to 1000m, it communicates directly with the SBC using RS-232 serial protocol.

3.6.5 Hydrophones

Four Reson TC 4013 hydrophones are used as an input array to receive the pings of an active sound source emitting at regular intervals.

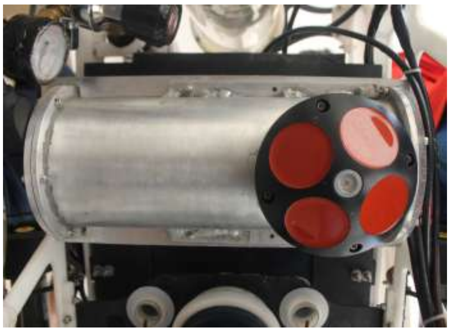


Figure 13: *Teledyne RDI's Doppler Velocity Log with its enclosure*

With an input sensitivity of -211dB ± 3dB re 1V/uPa and usable frequency range of 1 Hz to 170 kHz, these hydrophones provide an optimal solution for a passive acoustic localization system.

4 Software

The Software Stack of Matsya 4A has been developed on top of Robot Operating System (ROS), developed at Willow Garage.

The software system is implemented as one stack with different packages representing various modules like vision, navigation, controls, firmware and mission planning. The design specifications of the stack ensured that it is extendable, independent and generic. ROS helped in meeting these design goals and keeping the software modular with different tasks compartmentalized into various processes called nodes. ROS handles all the Inter Process Communication between the nodes via messages and services. The software can scale with respect to the tasks or missions that can be accomplished. It is also generic enough to be plugged into other robotic frameworks. The broad division of the software stack into different levels is as follows:

- Off-Board Computing: This layer consists of specialized hardware like filters, amplifiers, ADC, GPIO, etc. The communication with SBC is over TCP/IP and UDP protocols.

- Firmware/Driver Layer: Responsible for all of the Hardware Abstraction, this layer helps abstract data from the sensors and present them as processes to the SBC.This layer also consist of abstracted module for handling GPIOs, PWMs and ADCs. Each hardware peripheral connected to the SBC is abstracted out as a ROS node.

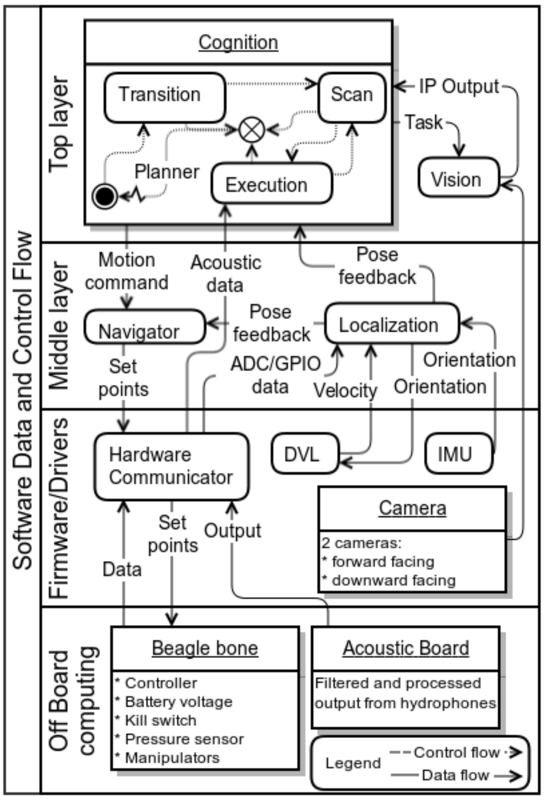


Figure 14: *Software Data and Control Flow*

- Middle layer: This layer is responsible for processing information from sensors such as IMU, DVL and Cameras and presenting it to the higher level logic nodes.

- Top layer: This layer uses information from the middle layer to generate actuation commands. It also provides a real-time interface to monitor Matsyaś performance and as well as to implement individual missions.

4.1 Localization

The localization module targets clear segmentation of upper layers of cognition and lower layers which consist of different sensors and controller driver modules.

It is responsible for filtering and fusing data from inertial and acoustic sensors to provide the top layer with a single source of all relevant localization data. At all points of time, Matsya uses the localization data to localize itself in the belief map.

4.2 Inter Board Communication

The number of boards has been reduced by using an on board controller (Beaglebone Black) which has an ARM microprocessor on board. The communication between SBC and on board controller is handled over TCP/IP and UDP protocol which provide a reliable mechanism for transferring of data. A server running on the controller handles all the incoming communications from SBC, where one node acts as the client. A similar architecture exists for communication with the Acoustic Localization System.

4.3 Navigation

The Navigation system is responsible for converting motion primitives generated by the Top layer to set points understandable by the lower layers. It handles the generation of set-points for intermediate locations on the trajectory generated for motion from point A to point B. Based on a state machine architecture, it chooses the motion to be performed based on checks on the localization data with respect to the desired set point.

4.4 Mission Planner

The mission planner controls active behavior of Matsya. Its main goal is to schedule tasks depending upon the active state of the system to maximize the score in the competition. To achieve its objective, it runs a state machine which consists of 3 states for each task:

- Transition State: When the currently active task is not in the range of Matsyaś sensors, Matsya navigates to the optimum point using a user-fed belief map. As soon as Matsya has the task within range of its sensors, it switches to the Scan State.

- Scan State: When the currently active task is in the range of Matsyaś sensors, Matsya tries to search around itself using a combination of its history and user-fed scan plans. Using its sensors, it tries to cover the most probable region for the currently active tasks till it receives an acceptable amount of sensor feedback. On reaching an acceptable position to perform the task, it switches to the Execution State. If it fails to find the location of the task within pre-specified time it aborts the current mission

- Execution State: When Matsya enters the Execution State from Scan State, there is a very high probability that the task can be completed. In this state, Matsya performs the required motions to complete the task, and moves onto the next task on successful completion. On losing track of the task, it switches to scan state so as to position itself properly again.

  Figure 14 describes the state machine and the various transitions.

4.5 Interfaces

Quite a few improvements were done to make the user interfaces robust, modular and intuitive to use with a few ROS utilities added to them.

- **Debug Interface**

  This aids in the complete manual navigation of Matsya and helps in resolving both minor and major errors during testing. It also incorporates some task related parameters which are essential and form a core part of Matsyaś run. The underlying idea behind developing Matsya 4A's Debug Interface was to provide the user maximum control over Matsya and to allow task execution with fewer button clicks, as well as easier modification of parameters to be viewed or controlled. This demanded for a responsive and modular UI which was met using the rqt plugins.

Figure 15: *Debug Interface*

- **Vision Interface**

  This interface is used to set various vision related parameters which are to be tuned depending on the environmental conditions.

- **Map Interface**

Provides a drag and drop interface to schedule a list of tasks to perform on an estimated map of the arena. The output of the map is used by the mission planner for navigating from one task to another and for real-time tracking of Matsya with respect to the tasks in the arena.

4.6 Vision

The vision subsystem provides crucial information about the target object which is used for navigating Matsya to the target location and performing the desired mission. Software modules for image processing and computer vision are built using Intel's OpenCV 2.4 library.

- Framework: The image processing code is implemented as a library employing object oriented philosophy for different processing techniques. Since the other software elements are entirely based on ROS architecture, a single vision node in ROS environment is used to handle the communication between vision and other software elements. This helps in reducing the inter-process communication delays which might occur in ROS and thus complex algorithms can be used in the vision subsystem.

- Camera control and pre-processing: To account for the varying environmental conditions such as illumination variation, brightness artifacts, sunlight reflection, etc., auto exposure and gain control algorithms have been implemented which update the camera parameters in real-time. Also, several localized and adaptive pre-processing techniques have been developed to handle water color cast, poor contrast, and reduced color quality underwater.

- Processing techniques: The major processing modules include color detection, shape based validation, region growing, contour analysis and machine learning based object detection and classification. A modular framework has been developed for video-based object training and model generation. Each task object is detected by a combination of aforementioned processing techniques. The final output of the processing module gives generic information about the target such as its location, orientation, dimension, distance-to-camera estimate and some task specific information. This information is communicated to other software elements via the Vision ROS node.

- Parameter tuning: Some of the image processing techniques require some tuning of parameters for better performance. Thus, an easy-to-use GUI based parameter tuning interface has been prepared which can be used for the live update of the parameters.

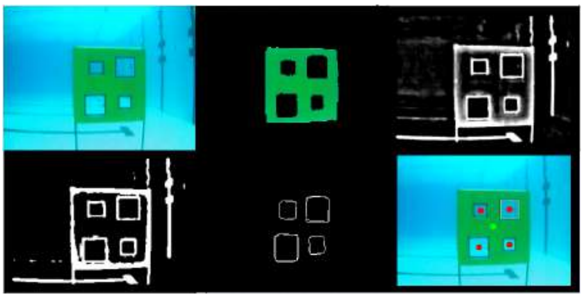


Figure 16: *Torpedo Cutout Detection*

One major addition in Matsya 4A is a generic object tracking algorithm which is able to track the target object even if the detection techniques fail. Thus, a combination of object tracking and object detection algorithms has significantly improved our task execution capabilities.

4.7 Controls

This year Matsya's Motion Control System has been redesigned to provide precise control for five degrees of freedom, namely, surge, sway, heave, pitch and yaw. The control loop runs at a frequency of 10 Hz, acquiring localization data from the DVL and IMU and generating appropriate PWM signals for each of the six thrusters. A cascaded control architecture has been developed which comprises of a kinematic controller and a dynamics controller. The kinematic and dynamic controller pair is able to achieve global position and velocity reference tracking.

A 3D motion simulation tool has also been developed to analyze the performance of the motion controller. This tool is also used to test our motion planning and navigation techniques.

5 Conclusion

With much rigorous design, analysis and testing done by all the three divisions of the team, Matsya 4A has the ability to easily adapt and incorporate additional systems integration without major developmental changes. This will help the team to focus more on software testing and sorting out runtime issues efficiently in future. Innovative indigenous solutions like underwater connectors and switches provided unique insights into the team's design philosophy. With major advancements in software and electronics architecture to incorporate DVL and Acoustic Localization system in the navigation framework, Matsya 4A offers a great opportunity to the team to pursue further its research in Underwater and Autonomous Robotics.

6 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 sincerely appreciate the generous support from our sponsors. They played an instrumental role in helping us meet our goals within our budget constraints.

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