Research and Development of Matsya 3.0, Autonomous Underwater Vehicle

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Abstract—Matsya series of Autonomous Underwater Vehicles are being developed at IIT Bombay with the aim of making a research platform in the field of underwater robotics and to promote autonomous systems. Since 2011, the AUV-IITB team has developed three vehicles each one much more advanced and capable than its predecessor. The latest vehicle, Matsya 3.0 has its design philosophy similar to Matsya 2.0 except for the provision of high modularity, enabling easy integration and removal of components, sensors and sub-systems. The electronics and software architecture has been significantly improved to incorporate DVL and Acoustic Localization Unit in the navigation framework of the vehicle.

1 Introduction

Matsya 3.0 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 Doppler Velocity Log and Acoustic Localization Unit, 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 specialisations having a strong motivation to explore the field of Underwater Robotics. It has four subdivisions namely Mechanical, Electronics, Software and Image Processing. Matsya 3.0 has seen a year-long development cycle with majority of components, underwater connectors and electronics boards designed in-house by the team members.

Figure 1: *Matsya 3.0*

2 Mechanical

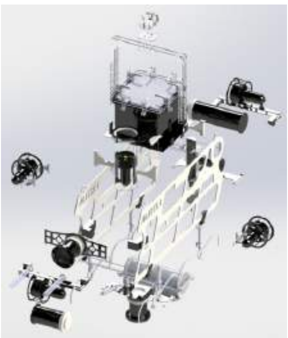
The Mechanical system of Matsya 3.0 is developed on the same framework as that of previous generation vehicles with added provisions for integration of DVL and hydrophone array. The dimensions of the vehicle are $1150 \times 660 \times 640mm$ and weighs 42 kg. The structure consists of vehicle frame, main hull and external enclosures for batteries, cameras, IMU, DVL and actuators.

During the design phase, a lot of emphasis has been given on the accessibility of different enclosures and attachments. The vehicle is mechanically stable in roll-pitch axes and highly optimised for strength and buoyancy.

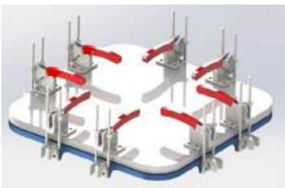
2.1 Hull

Main hull is the central pressure chamber of the AUV meant to provide a watertight region for the electronics of the vehicle. Design objectives for the main hull include robust water-proofing, ease of assembly and disassembly in wet state and efficient heat circulation. The hull is cuboidal in shape with dimensions of $270 \times 250 \times 210mm$ to ensure compactness with ready access to the electronic stack.

All the electronics boards are assembled together in a custom designed acrylic rack for compactness and high accessibility. Main Hull comprises of three parts: Baseplate, side wall and upper flange. These parts have been welded together to reduce the machining and material cost while meeting the strength and waterproofing requirements. Al 5051-O has been used for the side wall due to its high ductility and good thermal conductivity while Al 6061-T6 has been preferred for flange and the base plate because of its relatively high strength factor among other aluminium alloys. An acrylic end cap at the top provides a transparent interface for visual detection of water seepage as well as electronic displays and indicators. The flange is designed to avoid accumulation of water on the top surface and to ensure that no water seeps inside the chamber during disassembly.



(a) *CAD rendered exploded view of Matsya 3.0*



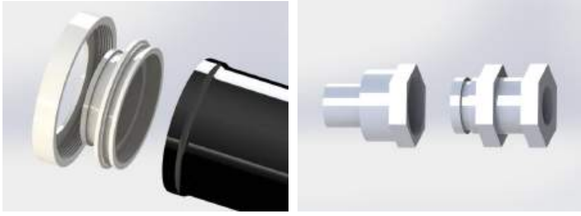
(b) *End cap*

(c) *Flange*

Figure 2

Pull-action toggle latches are mounted on the end cap for mechanical squeezing of Nitrile O-ring between the flange and the end cap. Separate enclosures are designed for batteries, pressure sensor, cameras and IMU to provide modularity to the system.

Connectors The team has fabricated in-house six pin underwater connectors to route connections between different waterproof enclosures, thrusters and sensors. The connector body is made up of an aluminium bore in-



(a) **(b)**

Figure 3: *(a)Design of End Cap for Battery Pod; (b)Connectors*

tegrated with an O-ring. The plug and play nature of these connectors makes it convenient to integrate additional systems in the vehicle and eases the phase of disassembly and replacement. The manufacturing cost for these connectors is twenty times cheaper as compared to the market.

Penetrators Penetrators are designed to route the cables out of the hull for direct connections to the sensors for which the simple plug and mate connectors cannot be used due to data loss and impedance matching problems.

Underwater Switches Underwater switches are developed to reset the electronic system, switch between different mission states and to kill the power from outside. These are based on rotatory shafts which have two glands for O-rings and operate under dynamic shear. The depth of the gland is smartly designed to ensure waterproofing and the portion between the glands is filled with silicon grease for smooth rotatory motion.

Latches For sealing the Main-hull, pull action toggle latches are fixed over the acrylic end cap using threaded inserters to squeeze the O-ring sandwiched between the end cap and hull body. Locks composed of e-clips and springs are mounted on each latch to avoid accidental opening under water.

2.2 Frame

The frame of Matsya 3.0 is responsible for providing a rigid structure to the vehicle's peripherals. The positioning and mounting of these peripherals have been done strategically to develop a bottom-heavy open-frame structure which exhibits symmetry, modularity and stability. An open frame structure ensures easy and fast accessibility and inspection of any component of the vehicle. To make the vehicle dynamically stable, the position of the peripherals have been estimated so as to align the Centre of Buoyancy (COB) and the Centre of Mass (COM) vertically, with COM lying below COB.

The design consists of an exterior delrin based frame, which supports an interior Aluminium 6061- T6 frame and also plays the role of shrouding critical components. Bolts and nuts have been used for mounting peripherals and connections to avoid orientation defects caused by welding. IMU is placed outside the main hull in a separate enclosure attached with the external frame in order to eliminate electronic noise inside the main hull. Thruster mounts are designed such that the wake of thrusters doesn't produce any skin friction drag on side frame of the vehicle. Heave thrusters have ducts around them to ensure similar flow condition. All structural elements of the frame have been analysed using Finite Element Method (FEM) before fabrication using a 3 axis CNC machine.

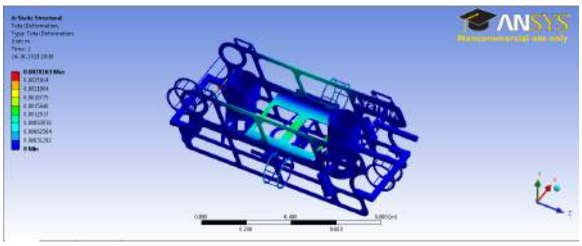


Figure 4: *Frame analysis in ANSYS*

Thruster Positioning and Profiling The vehicle uses six Seabotix BTD150 brushed thrusters to navigate along 5 degrees of freedom, namely pitch, yaw, surge, heave and sway. The centre of drag, determined by the centroids of the effective surface areas of the vehicle has been aligned with the plane of thrusters to prevent undesirable pitch motion. The surge and sway thrusters are strategically placed to make their plane coincide with the horizontal plane passing through Centre of Gravity (COG) of the vehicle. This avoids angular moment along roll and pitch axis providing optimum yaw and surge control. All thrusters have been profiled in a controlled environment to determine their characteristic thrust forces with respect to the voltages provided. These thrusters are rated at 110W maximum power and are capable of providing a continuous thrust of 2.2 kilogram-force (KGF) with a peak thrust of 2.9 KGF resulting in vehicle's maximum speed of 0.5 meters/sec. Thruster profiling has helped in developing a precise model of the vehicle to calculate the control parameters.

2.3 Actuators

A centralized pneumatic system has been adopted for managing all the actuators of the vehicles. This consists of a standard paintball CO_2 tank and a regulator, which provides a constant pressure of 100 PSI to all the pneumatic actuators. The control valves used are of two types- 5/2 valves and 2/2 valves. The 5/2 valves are used to actuate marker dropper and gripper while the 2/2 valves are used to shoot torpedoes. These valves operate at 12V DC with a maximum power output of 2W.

Gripper Matsya 3.0 has four grippers mounted on the frame of the vehicle. The length of the lower part of gripper is kept to be 28 cm which provides a gripping area of nearly 1000 square centimetres. Each assembly is actuated using a piston driven by a 5/2 valve coupled with a speed regulator providing a steady and stable actuation.

Figure 5: *Gripper Design*

Marker Dropper The pneumatic piston in a marker dropper is actuated using a solenoid valve to drop the marker supported on the shaft of piston. Each marker is 3D-printed using ABS thermoplastic and a steel ball is embedded in the head during the printing process. The deviation in marker's trajectory, in an 8 feet column of water, flowing with a speed of about 0.5 m/s has been found to be 2 cm.

Torpedo Like the marker droppers, the torpedoes have been fabricated using 3-D printing with ABS thermoplastic. A small brass rod is inserted axially in the head of a torpedo to provide stability and make it neutrally buoyant. After various design iterations, fins were tilted to a 10 degree angle to gain maximum linear traversing stability. The outer body of torpedo is a combination of hemispherical front and parabolic cone back. Slenderness ratio has been kept as 5.9.

3 Electronics

While designing the Electronics Architecture of Matsya 3.0, the focus was on the development of a generic and robust electronic system for underwater environments. The architecture has been designed to be modular enough to integrate different sensors and devices according to the specific requirements. Provisions have been given for adding most of the critical components, sensors and subsystems for underwater purposes like acoustic positioning unit, water seepage detection and Doppler Velocity Log (DVL) so that the system can be used in most AUVs without major design changes.

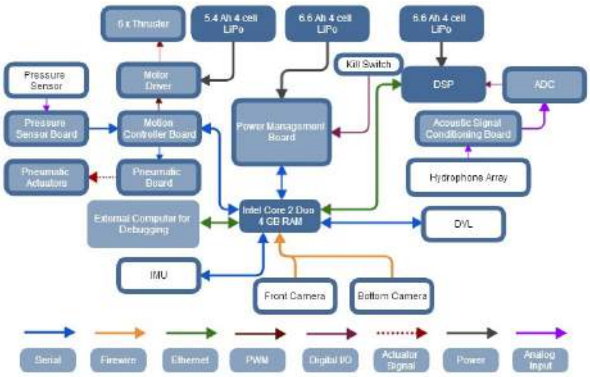


Figure 6: *Electronics System Communication Diagram*

3.1 System Design

UART (TTL and RS-232), commonly known as a serial protocol is used for communication among major subsystems. This protocol was chosen because of the simplicity in interconnections and possibility of standard character transmission format. IMU, DVL and other major sensors provide data to the Single Board Computer (SBC) using RS-232 protocol. I2C bus has also been implemented for modularity and protocol extension for some devices.

3.1.1 Single Board Computer (SBC)

The core processing unit of Matsya 3.0 consists of Axiomtek's mini-ITX motherboard powered by an Intel Core 2 quad 3 GHz processor with 4 Gigabytes of RAM. Though the computational requirements due to complexity of tasks have been increased manifold this year, the current SBC, also used in Matsya 2.0 manages to perform the specific tasks efficiently.

(a) *SBC86860* **(b)** *Central Board*

Figure 7

3.1.2 Central Electronics Unit

Being the single largest custom-designed board on Matsya 3.0, this unit in coordination with the SBC performs major tasks like power management, execution of control loops on individual thrusters and actuation of pneumatic devices while incorporating various fail-safe features like water seep-in detection for most of the pressurized vessels of the vehicle and LED array for debug and diagnostic purposes. The entire electronic system can be easily removed from the AUV as a single stack for ease of access.

All the controllers on the system are separated out of the central unit using custom designed boards. This approach provides the ease of faulty controller replaceability, off-board programming and accumulating the same number of components in a relatively much smaller area.

Power Management System The Power Board performs the task of regulating power for all the sub-systems of the vehicle while incorporating various other features like short circuit protection, reverse battery polarity protection with voltage measurement, data logging to a SD card and RGB LED array for debug and diagnostic purposes. Standard voltages 3.3V, 5V and 12V are accessible from a power rail ensuring that the voltage requirements for most

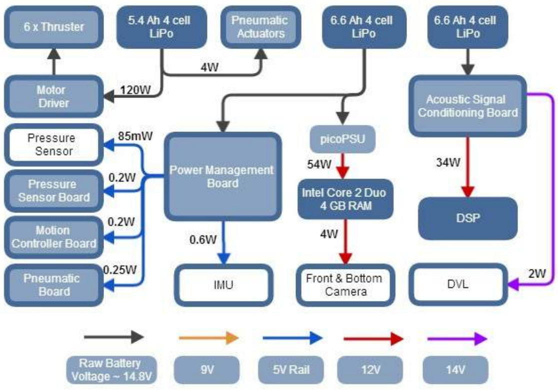


Figure 8: *Power Distribution Diagram*

of the standard industrial sensors are met.

Motion Controller As per the set-points provided by the SBC, Motion controller board executes closed-loop control algorithms providing the desired PWM outputs to individual thrusters. Maintaining the logic level compatibility, entire system can operate at 5V logic level as well as 3.3V without reiterating the design process. The controller functions inline with the pneumatic and the pressure sensor boards by passing instructions for actuating pneumatics and for calibration of pressure sensor. An RGB array is given for the visual status of mission critical parameters such as the vehicle's navigational status.

Programmer- USBasp There are on-board custom-made USBasp programmers for programming micro-controllers via SBC so as to eliminate the need of plugging-in external programming devices. USBasp is a USB in-circuit programmer for Atmel AVR controller family. It consists of Atmel's Atmega8 microcontroller, a couple of passive components and integrated circuits for protocol conversion.

3.1.3 Pneumatic Board

The Pneumatic Board provides the functionality of independent operability of the pneumatic actuators without affecting the other subsystems. This board receives commands from the motion controller for the purpose of firing torpedoes, dropping markers and object manipulation. There are 6 solenoid valves which can be switched independently using a microcontroller driven solenoid driver-LMD18400 from Texas Instruments. The pneumatic board also consists of a motor driver for driving Stepper or Servo motors.

3.1.4 Pressure Sensor Board

Placed compactly inside the pressure sensor hull, this board converts the analog readings of the pressure sensor to digital values and sends them to the motion controller board via serial communication.

(a) (b) (c)

Figure 9: *Power, Motion Controller and Pressure Sensor Boards*

3.1.5 Water Seepage Detection Unit

These are custom modules designed to detect water seepage in the most critical vessels of the vehicle like the main hull and DVL enclosure. It consists of two fine mesh grid structures made up of aluminium, separated by a very small distance. Even a small water droplet is capable of closing the circuit between these two grids, thereby triggering an external interrupt of the power board.

3.1.6 Motor Driver Board

The Motor Driver Board integrates all the 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.

3.1.7 Acoustic Localization System

Acoustic localization unit of Matsya 3.0 uses two hydrophones to localize the vehicle with respect to an active sound source. The entire system's execution is divided into five stages mentioned below with the first four stages being executed on a custom-designed board.

- Pre-Amplification: This stage involves the pre-amplification of raw hydrophone signals that intrinsically have very low peak to peak voltages. The gain is digitally

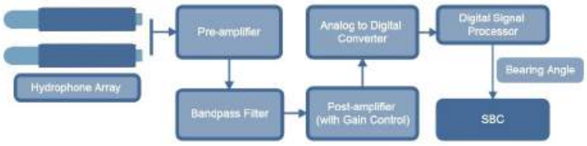


Figure 10: *Acoustic Localization: Five stage process*

controlled in order to compensate for voltage compatibility with ADC levels and improve sensitivity. Texas Instruments OPA 209 and 211 are used for amplification purposes due to their high gain-bandwidth and slew rates.

- Filtering: An eighth order ellyptic bandpass filter is used to remove most of the noise from the amplified signals and pass them to the post amplification unit. Maxim's MAX274 continuous time-active filter is used in this stage with its separate filter sections cascaded 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 Analog to Digital convertor voltage levels.

- Analog to Digital conversion: The post amplified signal is fed into a 14 bit ADC for sampling purpose and each sample is serially transmitted to a digital signal processor using synchronous communication. Analog Devices AD7367 ADC is used for this purpose with sampling rates up to 200KSPS.

- Digital Signal Processing: Texas Instruments TMS320C6670 1.0 GHz quad-core Digital Signal Processor is used for acquiring data from ADC at high speed and for final processing of the signals for calculation of bearing angle to the pinger. Due to availability of a large section of Memory on board, entire signals are stored at once and then analysed to estimate heading of the sound source. The Ethernet boot option of the DSP helps to transfer the acquired data at high speed to the SBC resulting in a faster update rate of the bearing angle.

Figure 11: *Custom Designed Acoustic board integrated with DSP Evaluation Board*

3.1.8 Batteries

Matsya 3.0's entire system is powered by three 4-cell 14.8V 45C Lithium Polymer batteries from Thunderpower RC. A 5.4Ah capacity battery is used for thrusters and pneumatic actuators while the other two 6.8Ah batteries are used for powering electronic system and the acoustic localization system respectively. With all mission-critical tasks running along with the onboard peripherals, these batteries gives an endurance of about 1.5 hours to the vehicle.

3.2 Sensors

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

3.2.1 Cameras

Matsya 3.0 uses two Unibrain Firewire colour cameras for its machine vision. The vehicle's bottom view camera is a Fire-i 1394a board camera while the front view camera is a Fire-i 580c 1394b industrial camera. Based on ICX-625 Sony CCD sensor, these cameras provide various features like high resolution colour video streaming at adequate frame rates, multi-camera synchronization and realtime 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).

3.2.2 Inertial Measurement Unit

For low-drift and precise orientation measurements, Matsya 3.0 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 mag-

Figure 12: *Firewire-800 Industrial Camera*

netometer 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.

3.2.3 Pressure Sensor

US381 pressure sensor manufactured by Measurement Specialities Inc., is used for the vehicle's depth measurements. With an operating pressure range of 500 PSI, this sensor outputs current in 4-20 mA range proportional to the pressure exerted on its outer diaphragm.

3.2.4 Doppler Velocity Log

Teledyne RDI's Explorer Doppler Velocity Log (DVL) is a major addition in the electronics sub-system of Matsya 3.0 and has significantly improvised its navigation and localisation framework. By fusing data from onboard inertial and depth sensors, 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 standard.

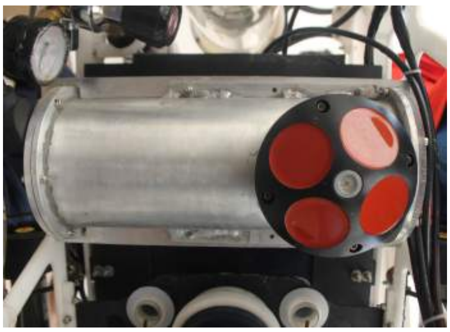


Figure 13: *Teledyne RDI's Doppler Velocity Log with its enclosure*

3.2.5 Hydrophones

Two Reson TC 4013 hydrophones are used as an input array to receive the pings of an active sound source emitting at regular intervals. 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 3.0 has been developed on top of ROS (Robot Operating System), developed at Willow Garage. Also, the Gazebo simulator has been used to test the software before deploying it on the vehicle. The software system is implemented as one stack with different packages representing various modules like vision, navigation and mission planning. The main design goals of the stack were to keep it extendable, independent and generic. ROS helped in meeting these design goals and keeping the software modular with different tasks clearly demarcated and distributed into various processes called nodes. The modules are entirely independent of the internal implementations of each other and communicate through special data types called messages. The software is easily scalable with respect to the tasks or missions that can be accomplished. It is generic enough to be plugged into other robotic frameworks. The broad layers of the software stack are as follows:

- Firmware: The lower most layer running on micro-controllers
- Middle Layer: Responsible for Inter Process Communication (IPC) and Hardware Abstraction. The middle layer helps abstract data out of the micro-controllers and presents them as processes to the SBC. Each hardware peripheral connected to the SBC is abstracted out as a ROS node. ROS handles all the Inter Process Communication by means of messages and services.
- Processing Layer: Responsible for processing Information from sensors such as IMU, DVL and Cameras.
- Application Layer: Uses information from the processing layer to generate actuation commands. It provides a real-time interface to monitor the vehicle's performance and to implement mission planning.

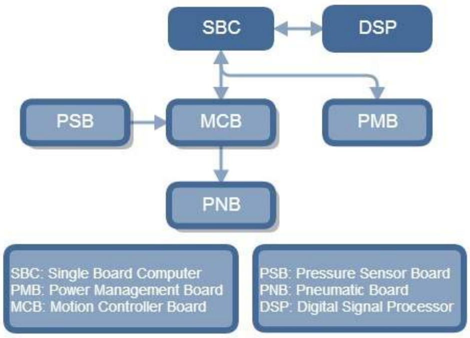


Figure 14: *Inter Board Communication*

4.1 Localization

The objective is to autonomously navigate the AUV using visual, inertial and DVL as the only sensors. The localization problem involves locating the vehicle on a map, with respect to its starting position. This task involves taking measurements and correcting them depending upon the localization handled by the localization stack, which incorporates the IMU (Inertial Measurement Unit) & DVL (Doppler Velocity Log) to find its precise location. Detecting landmarks through visual feedback is a standard approach to correct drifts in measurement by the sensors.

4.2 Inter Board Communication

The communication stack is responsible for enabling data and command transfer between six different boards on the vehicle. The boards are connected via a RS-232/UART or Ethernet in a tree like structure as show in Figure 14. All boards are mutually connected (directly or indirectly) enabling communication between them.

The communication between any two boards is based upon a "ping & reply" system. A board close to the root of the tree initiates communication between any set of two boards. For example, SBC would initiate communication with the MCB. The communication between two boards is dual.

4.3 Navigation

Navigation system is needed to perform manoeuvring tasks for a given trajectory. Navigation involves two task, giving actuation commands and making corrections using feedback from localization. From previous software versions, the team had learnt about the problems faced when a higher layer (in this case the mission planner) interacts with lower layers such as controllers. So, need was felt to provide a common platform where all the Task Executors could launch commands which were lucid. This has reduced a lot of load from the programmer perspective.

The Navigator is implemented as a state Machine which achieves its goals in stages. Given two points A & B, the navigator is instructed to move towards B from A, the line of motion taken by the vehicle is thus the line joining the two points, provided that the depths of the two points are the same from surface. With accurate position measurements from localization, the navigator attempts to steer the vehicle to maintain its position or achieve a certain position.

4.4 Mission Planner

The mission Planner controls the active behaviour of the vehicle. Its main goal is to schedule tasks depending upon the active state of the system to maximize the score in the competition. Every task execution is divided into 3 phases:

- Transition State: The vehicle is in transition state when it navigates from one task to another using belief map which is user-fed. The vehicle keeps approximate track of its position and tries to localize itself according to the map. Whenever the vehicle is near the task it transitions to the next state, i.e. the Scan State).

- Scan State: The vehicle tries to search around itself for the specified scan plans for it to do. It tries to wander around in a small area to get an acceptable amount of visual feedback. When the AUV stabilizes and is in a better position to perform the task, it transitions into the next state, i.e. the Execution State. If the vehicle fails to find the location of the task for some specified amount of time it discards the current mission and moves to the next.

- Execution State: When the vehicle is in this state there is a very high probability that the vehicle will complete the task before it moves to the next. If the machine loses the track of the task then it enters back into scan state so as to position itself

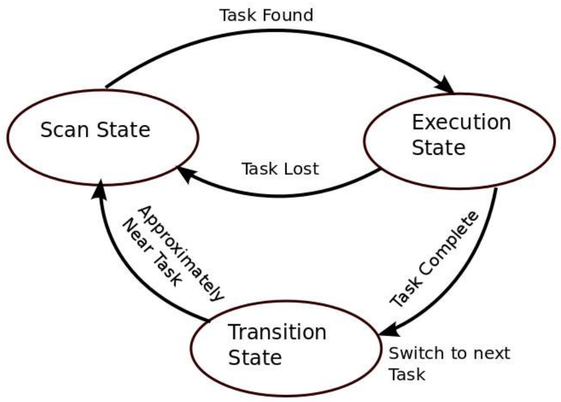


Figure 15: *Task State Machine*

properly.

At any point of time the AUV will be in one of these states. Figure 18 describes the transition conditions between the states

4.5 Interfaces

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

- **Debug Interface**

  This aids in the complete manual navigation of the vehicle 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 the vehicle's run. The underlying idea behind developing Matsya 3.0's Debug Interface was to provide the user maximum control over the vehicle and to allow task execution with fewer button clicks. This demanded for a responsive UI which was met using the latest features of the Qt 5 library.

- **Vision Interface**

  This interface is used to set various vision related parameters which are to be tuned depending on the lighting 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 to help navigate from one task to another. Apart from visual scheduling of tasks, this GUI map interface also gives a real-time tracking of Matsya 3.0 and its relative position to all the tasks and the arena.

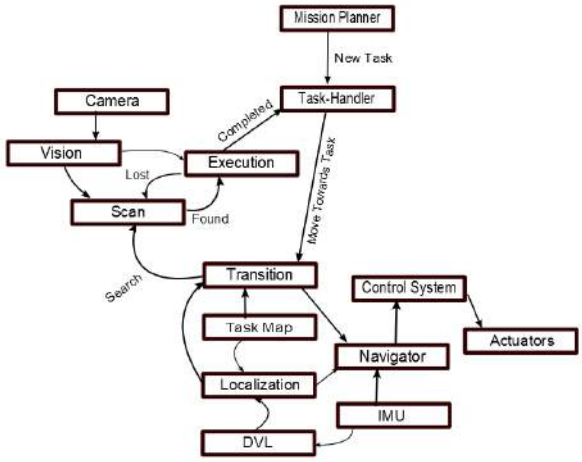


Figure 16: *Software Control Flow*

4.6 Vision

The task of vision subsystem is to provide crucial information about the target object which will be used for navigating the vehicle to the target and performing the desired mission. Software modules for image processing are built using Intel's OpenCV 2.4 library.

- Framework: The entire vision processing code is implemented as a single C++ library consisting of several classes 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 us a lot in reducing the inter-process communication delays which occur in ROS and thus computationally expensive algorithms can be implemented in the vision system.

- Camera Parameters control and preprocessing: In order 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 implemented to handle water colour cast, poor contrast, and reduced colour quality underwater.

- Processing techniques: The major processing modules implemented are colour detection, shape based validation, region growing, contour analysis and target tracking. One major addition in Matsya 3.0 is a machine-learning based object detection module which comprises of a sliding window detector, feature vector extractors and classifiers. It requires prehand training which uses several positive and negative training samples and generates a model file which can be later loaded for detection at run-time. Each task object is detected by a combination of several of these processing techniques. The final output of the processing module gives some generic information about the target such as its location, orientation, dimension, distance estimate and some task specific information.

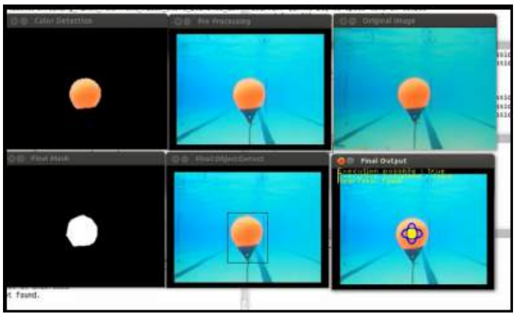


Figure 17: *Buoy Detection*

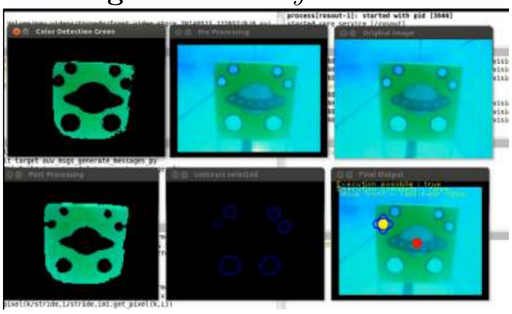


Figure 18: *Torpedo Cutout Detection*

- Parameter Tuning: Some of the image processing techniques require slight tuning of parameters for better performance. Thus, an easy-to-use GUI based parameter tuning interface has been prepared which can also display the effect of change of parameters on the live video output.

5 Conclusion

With much rigorous design, analysis and testing done by all the four subdivisions of the team, Matsya 3.0 has the ability to easily adapt and incorporate additional system integrations without major developmental changes. This will help the team to focus more on software testing and sorting out runtime issues efficiently in future. This year's vehicle design has been completely revamped to compensate for major sensor additions and dynamic stability issues. 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 3.0 offers a great opportunity to the team to pursue further its research in Underwater and Autonomous Robotics.

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