Design and Implementation of Amogh AUV

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***Abstract*—Amogh is the first Autonomous Underwater Vehicle (AUV) being developed by the students of Indian Institute of Technology, Madras. A multi-disciplinary undergraduate team has been working towards development of an underwater vehicle with maneuverability and control capability to solve problem statement set by AUVSI. Starting with a ROV design, the vehicle design was iterated at every stage envisioning a full fledged AUV to navigate through the tasks defined in the RoboSub competition.**

The proposed design is a modular hydrodynamic dual hull structure, supported with an aluminium frame. O-Ring face seals are used as temporary seals whereas anaerobic sealants are used for permanent sealing surfaces. The input feeds from two on-board cameras are processed to control and navigate the vehicle through the environment along with the orientation data from an IMU. A quad core atom processor i7-4470 does the required computing and an Arduino Mega2560 acts as the interface between the CPU and the payloads. Sensing solutions include a pressure sensor, an IMU, two on-board cameras and leak sensors. Propulsion system consists of 6 thrusters, powered using a bank of Lithium-Polymer batteries. One motor controller for each thruster permits differential control navigation. Pneumatics based mechanisms have been designed for certain tasks specific to the problem statement such as torpedo shooting and marker dropping.

I. Introduction

India's extensive coastline and near-shore waters contain biological and mineralogical resources. The exploration focus has shifted to these unexplored areas. We are determined to be a part of this technological advancement in underwater technology for exploration and inspection. With the focus and vision to design and develop a full fledged autonomous underwater vehicle, which specializes in exploration and inspection, we, team of undergraduate students from multiple disciplines, have cracked a first successful attempt to develop an AUV. It is the first student only developed underwater vehicle by undergraduate students in IIT Madras. Initial focus is to develop a vehicle to solve AUVSI RoboSub competition defined problem statement.

Design and construction of an AUV has numerous challenges to offer starting with water proofing. Static and hydrodynamic stability, propulsion, power consumption, control and navigation are other significant problems. A blend of technologies like image processing, artificial intelligence, remote communication, embedded systems, electromagnetics and pneumatics are employed in the vehicle. The design of Amogh can be grouped in three verticals mechanical, electrical and software.

II. Mechanical

Mechanical design module includes designing, prototyping and manufacturing of the various components of AUV. The major components include pressure hulls, actuation for the various payloads and structural frame of AUV. Each of the sub modules is explained in detail in subsequent sections. AUV is designed to be positively buoyant to a certain extent.

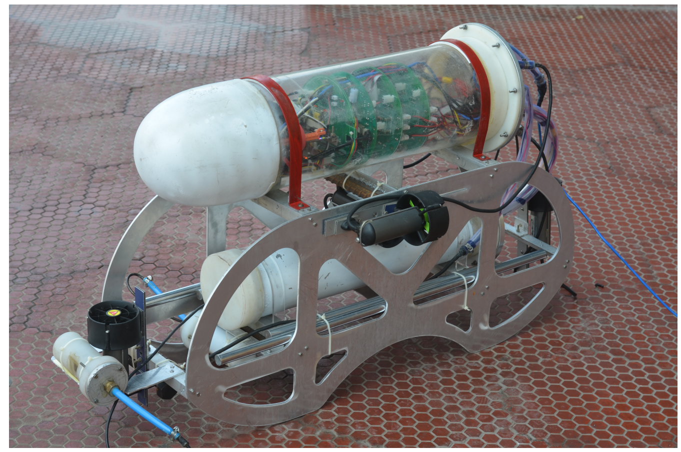

Fig. 1. Amogh AUV

A. Design of Pressure Hulls

Hulls provide a waterproof enclosure at atmospheric pressure for electronic payloads of the AUV. Generally several factors influence the design of the hull

- Static and dynamic stability of the vehicle.
- Modularity to allow upgradability in the design.
- Reduction of drag against velocity while in motion.
- Availability of sufficient space for the storage of batteries, electronics and other components.
- Ease of manufacturing.

Laying emphasis on the above stated points, a cylindrical shaped hull has been incepted in the design because:

- It is a good structure to resist hydrostatic pressure.
- It has a good hydrodynamic form which helps in reducing the drag on the vehicle.
- It provides sufficient space for placement of electronics.

Having finalized with the cylindrical hull shape, the following hull-thruster configurations were considered for the design of the AUV:

- Laminar Flow Design

- Torpedo Shaped Design
- Single Hull, Multiple Thruster configuration
- Dual Hull, Multiple Thruster configuration
- Dual Hull Design with Azimuthal Thrusters

The advantages and disadvantages of each design were reviewed and finally, the Dual Hull, Multiple Thruster Design was selected considering the static stability, dynamic stability and maneuverability requirements of the vehicle. Consider a

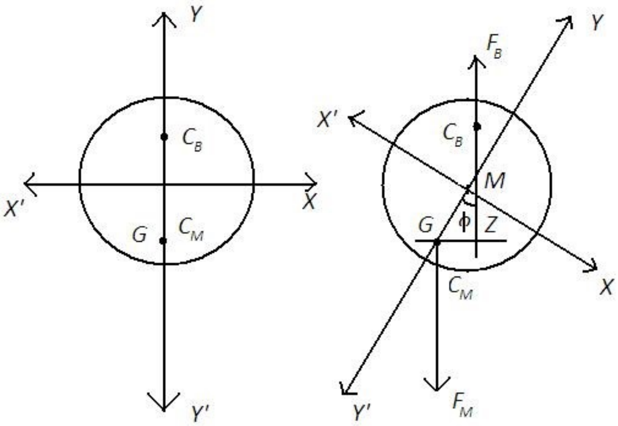

Fig. 2. Dynamics underwater

body fully immersed in water as shown in the Figure 2. It is stable when C_M and C_B are aligned and unstable when C_M and C_B are not aligned.

Therefore, when the body is unstable, a righting moment acts to restore the body in its stable position.

$$RM = (F_M + F_B) * GZ/2 \tag{1}$$

or

$$RM = (1/2) * (F_M + F_B) * (GM sin(\varphi)) \tag{2}$$

where F_M is the weight, F_B is the buoyancy, GM is the metacentric height and φ is the roll angle. So the given expression implies that greater the RM, i.e. greater the metacentric height, greater is the stability. By placing the batteries and other heavy components inside the lower hull and relatively light weight electronic components in the top hull, the vehicles C_M is lowered, increasing the vertical separation between the C_M and Centre of Buoyancy (C_B). This being heavy bottom design, inhibits the rolling motion.

To ensure communication between the two hulls, the end disks of both the hulls are provided with underwater SubConn connectors. The detailed description of the connectors is included in the later sections.

B. Material for the Hull

The hull material should have good resistance to corrosion, have a high strength to weight ratio and must be affordable. Considering above factors, acrylic plastic is chosen as the

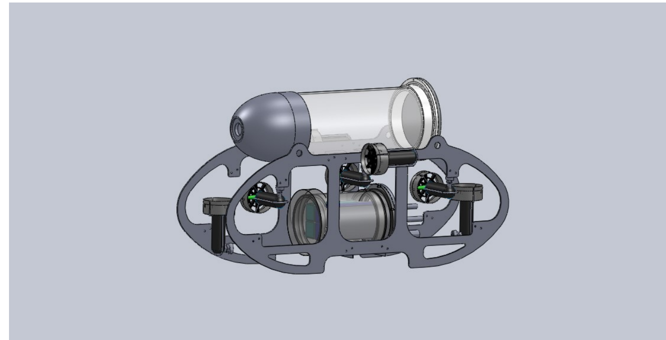

Fig. 3. SolidWorks CAD Model of Amogh

material for the top hull of the AUV. The added advantage of acrylic is that it is transparent allowing monitoring of the electronic components inside.

Bottom hull is made up of Stainless Steel which has a density of 8000 kg/m^3 to satisfy the needs of the heavy bottom design.

C. Hydrodynamic Shape

A hydrodynamic nose made of poly-propylene at the front end of the top hull has been used for minimizing the drag on the structure and hence to increase its overall speed without affecting the payload carrying capacity much. The options available for the shape of the front end cap shown in the figure 4 are given below.

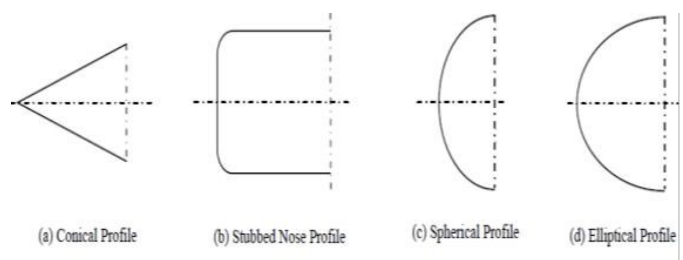

Fig. 4. Considered front end cap designs

The CFD analysis of each of the above shape inferred least drag coefficient in addition to least total drag (form drag + friction drag) for the ellipsoidal shape. Analysis of different major to minor axis ratios for the ellipsoidal front cap concluded the following points:

- Drag coefficient decreases as the ratio increases.
- Hence, speed of the vehicle increases with the ratio.
- Variation of total drag on the structure becomes constant after the ratio of 3.

D. Waterproofing Mechanism

Waterproofing is an integral part of any underwater vehicle design for protecting the electronics placed inside it. Face Seal Mechanism has been incorporated to fulfill the water sealing requirement of the AUV. A customized end cap with grooves to accommodate two rubber O-rings is attached permanently

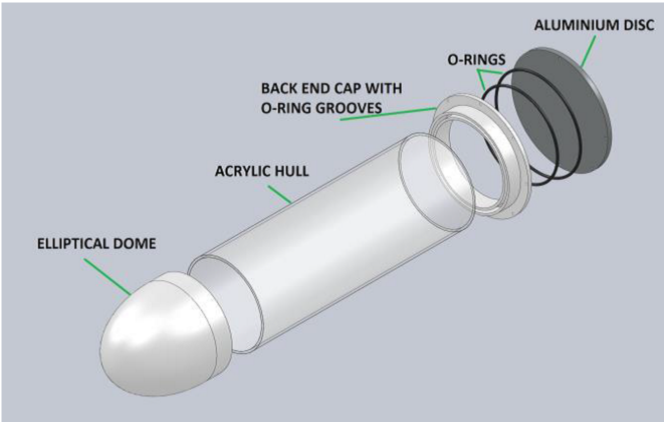

Fig. 5. Blowup of the hull

at the aft end of the top hull. It is covered with a flat disc, which consists of 8 co-axial holes, to mechanically squeeze the O-rings and to ensure water tightness. The circumferential gap between the end cap and the disc is sealed additionally using Silicon Grease.

E. Structural Analysis

A structural analysis of the hull was carried out for determining the appropriate thickness required for withstanding the hydrostatic pressure at a depth of $10m$. This was carried out using the simulation package of SolidWorks software.

The results obtained imply that 5 mm thickness of the hull is significant for it to withstand the operational pressure upto a water depth of $10m$.

The deformation obtained from SolidWorks Simulation were scaled up by a factor of 708.176, in order to make the deformation of the body visible. Higher the deformation scale, lower is the actual deformation.

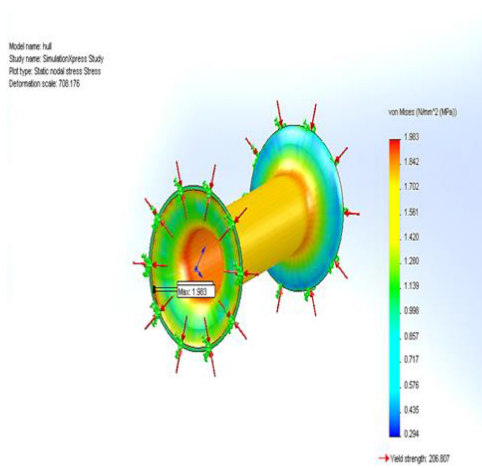

Fig. 6. Simulation Studies done to analyse the structural properties.

F. Frame

The frame constitutes the supporting structure of the AUV on which the peripherals are mounted. The material chosen for the frame was thin aluminium sheet because of its high strength to weight ratio and resistance to corrosion. Many designs of the frame have been developed and analyzed using the StarCCM+ software along with the main peripherals. Three dimensional Reynolds Averaged Navier-Stokes (RANS) equation was solved for velocity and pressure values in a domain with AUV inside it. The key factor for design of the frame is to reduce the drag in all the required directions of motion.

In order to estimate the resistance in the forward direction, the inlet velocities chosen were 0.5, 1 and 1.5 m/s for all versions of the vehicle. The obtained results have been compared and analyzed for change in performance.

Figure 8 shows different versions of the vehicle and the velocity contours of flow around them. The graphs in figures 7 and 9 show the variation of drag force and power required in forward direction contributed by different versions of the vehicle. The drag force split up of final design is shown in figure 10. The drag forces have been reduced by a significant amount in the final design.

The comparison of estimated resistance for different versions of the vehicle is shown in figure 7. The power required, ref. figure 9, shows that there is an intermediate reduction in power required by 19% from version 1 to version 2 and an overall reduction of power required by 35% from version 1 to version 3.

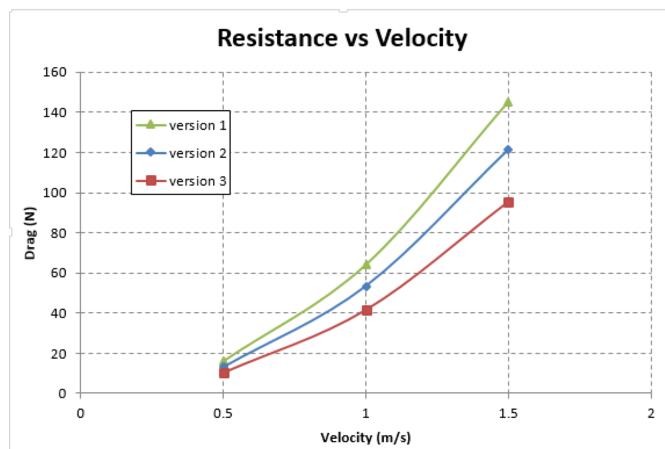

Fig. 7. Estimated resistance from CFD Analysis of different versions of Amogh

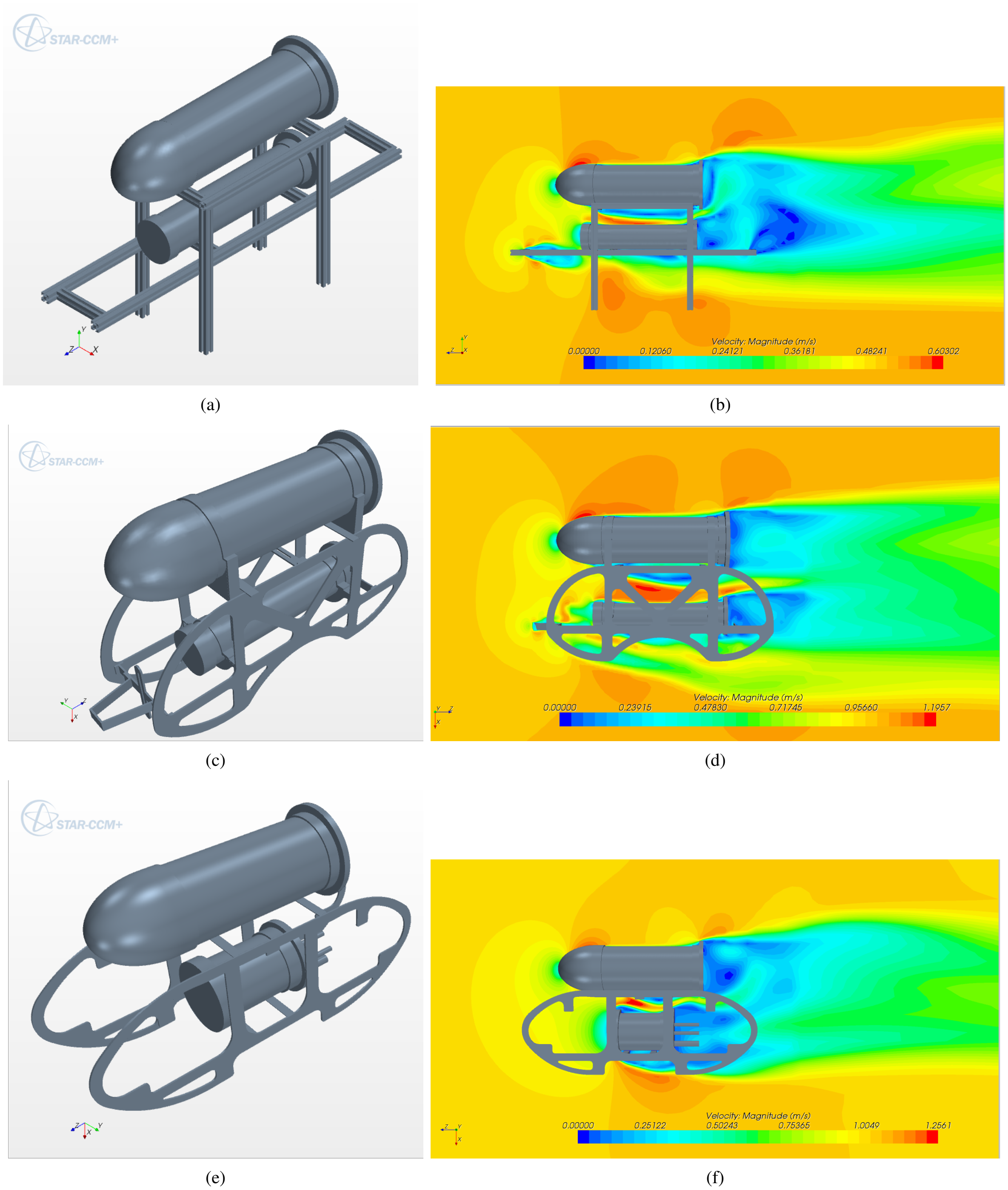

Fig. 8. Figure (a) (c) and (e) show different frame designs; (b) (d) and (f) show the velocity contour plot for the flow around the corresponding designs

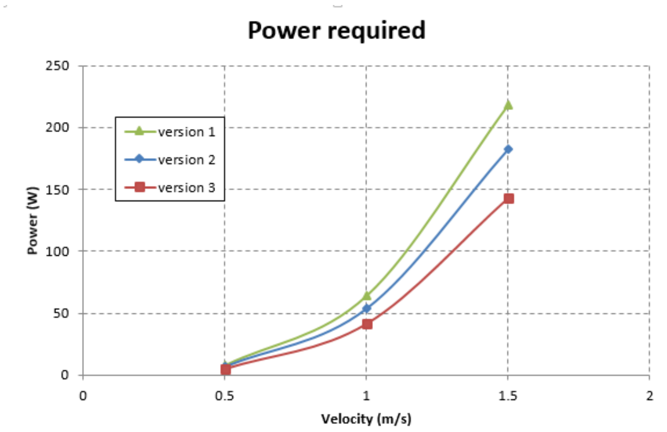

Fig. 9. Estimated power required from CFD Analysis of different versions of Amogh

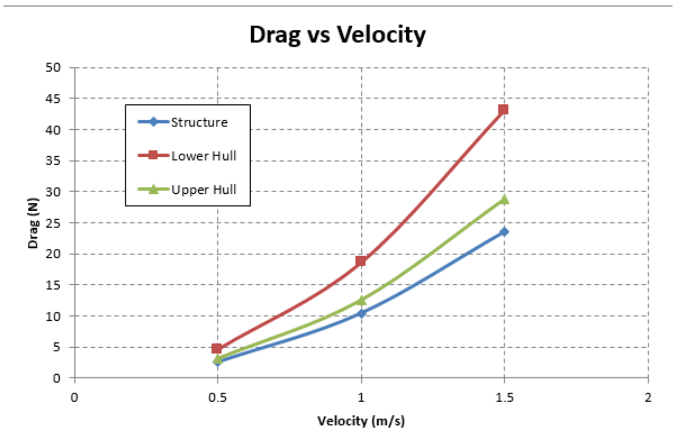

Fig. 10. Estimated resistance breakup of version 3 from CFD Analysis

G. Thruster Configuration

The vehicle uses 5 SeaBotix BTD150 thrusters for achieving control in 5 degrees of freedom. Two thrusters placed on either side of the frame provide independent surge motion control and also yaw motion control in the steering plane. A fore and an aft thruster mounted axially upwards provide Heave and Pitch control in the diving plane. The other two thrusters placed symmetrically on either sides of the line joining the CG and CB of the vehicle facilitate sway motion. The heavy bottom design of the AUV eliminates Roll motion. This thruster configuration is sufficient for effective maneuverability of the vehicle.

H. Torpedo Launcher and Marker Dropper

Torpedo: For accomplishing the objective of torpedo launching, following are the points to be considered:

- The torpedo should be neutrally buoyant.
- The design should provide least possible drag against motion.
- It should have fins for counteracting the moment applied by the drag force on its surface.

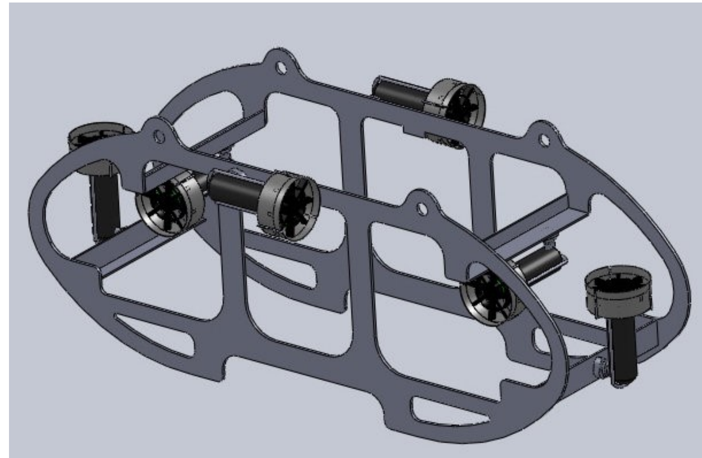

Fig. 11. Thruster Configuration

Fig. 12. Torpedo Design

- It should be able to cover a straight line path of at least 2-3 meters.

Hence, High Density Polyethylene (HDPE with mass density = $0.97kg/m^3$) was finalised for manufacturing the torpedo. Drag coefficient of the torpedo calculated using SolidWorks Flow Simulation was found to be 0.088.

Launching Mechanism: The mechanism used for launching the marker and the torpedo is based on pneumatic actuation. Pneumatics system of Amogh uses compressed air stored at high pressure inside a pressure tank. This pressure is regulated to a lower pressure of 8 bars by using a regulator.

Marker: In order to drop the marker in the bin accurately, the shape of the marker has been kept similar to torpedo(as seen in figure 13) and has been manufactured using Derlin. Compared to a spherical marker, this provides very low offset during a vertical fall as the fins counteract the torque which arises due to drag force on its surface. It also experiences less drag in comparison to spherical marker due to its ellipsoidal front and hence travels faster when released into water. A good hydrodynamic ratio of 1:5 has been maintained between diameter and length for this design. Weight concentration is higher towards the front which helps the marker to attain a straight trajectory underwater.

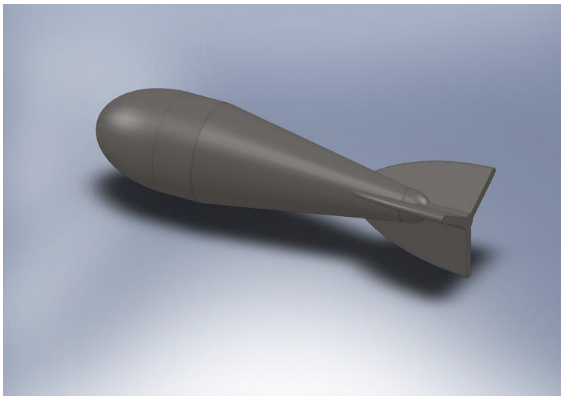

Fig. 13. Marker Model

Dropping Mechanism: The vehicle uses a pneumatic cylinder assembly for dropping markers. The piston is pushed back using a single acting cylinder, which is actuated using a solenoid valve, thus allowing the marker to fall in the bin. This design was chosen due to its low offset and high accuracy.

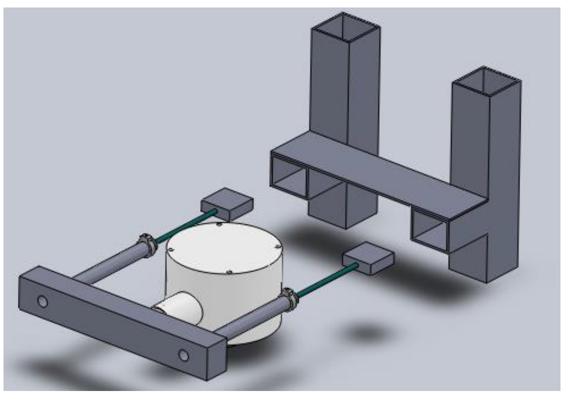

Fig. 14. Marker Dropper Assembly

I. Camera Enclosure

The AUV comprises of two cameras providing view ahead and below the vehicle, which facilitates the navigation of the vehicle. Hence, a transparent, watertight camera enclosure has been designed to enable the cameras to capture undistorted images. It is a cylindrical assembly manufactured with Nylocast material because of its ease of machineability into complex shapes. It is provided with a transparent acrylic sheet in front of the lens. A provision for a thin filter film has also been made in the design.

J. Connectors

To facilitate the interhull and ethernet connections, SubConn connectors have been used.

III. ELECTRICAL

The electrical sub-system facilitates control and navigation of the vehicle using mission software and helps keeping a track of the vehicle state using various sensors. This module comprises of a CPU, a Micro-controller, Power Supply Units,

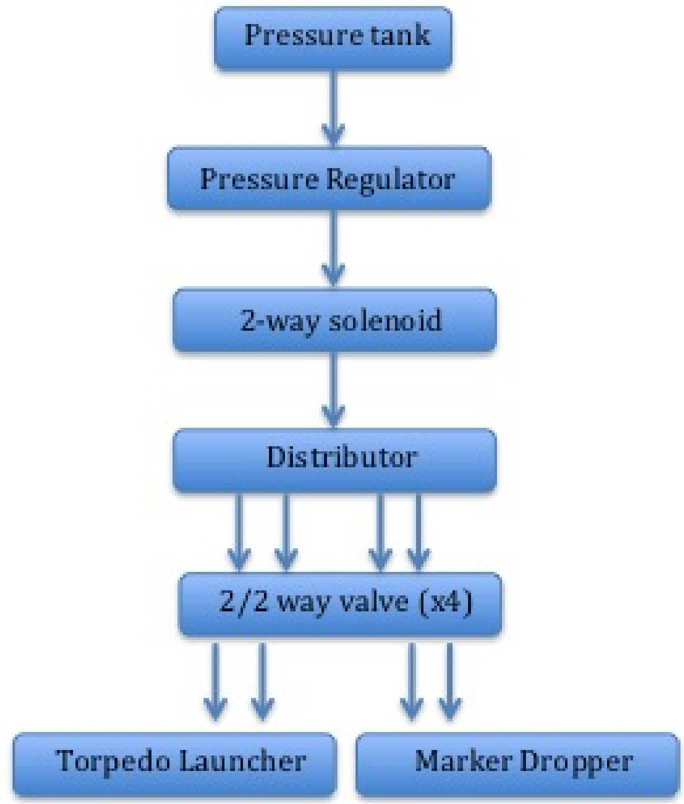

Fig. 15. Pneumatics Flow Chart

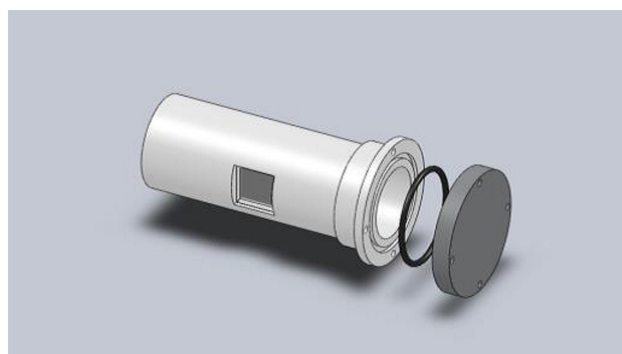

Fig. 16. Camera Enclosure

sensors and other essential electrical peripherals. Hardware used is in accordance with the demands of computing required for Image Processing and restrictions imposed by the power backup system to sustain the mission.

A. Motherboard

The motherboard contains majority of the principal components required for On-Board computing and serves as a hardware platform which facilitates communication between all components of the system. It contains the central processing unit and has provisions to connect to additional components/devices. Features include graphics processor, system memory (RAM), USB interface (serial/parallel), Ethernet for communication and arrangements to maintain the operating temperature. Additional features like Wi-Fi, serial expansion buses provide scope for upgradation of system without changing the motherboard. Amogh uses Intel's i7-4770 3.8GHz processor mounted on a MSI Z87I AC motherboard loaded with a 4GB DDR3 RAM.

Motherboards requires a non-fluctuating and uninterrupted DC power supply to deliver optimum performance. A miniature DC-DC ATX power supply - Pico PSU 120 manufactured by Minibox has been used to draw power from a bank of Li-Po batteries and supply to the motherboard. The PSU is capable of supplying continuous power up to 120 W at 12 V supply.

Fig. 17. Mother Board

B. CPU

The computational requirements are met using Intel's i7-4770T, a quad core 4th generation processor with a maximum Thermal Dissipation Power (TDP) of 45 W. The processor features 4 cores 8 threads and operates at 2.5 GHz. This is much higher as compared to our previous processor, which was a dual core Intel Atom D2700 with a TDP of 10 W and operating at 2.13 GHz. The CPU is supported with 4GB of DDR3 RAM on-board. This upgrade was made to speed up the complex vision processing algorithms.

C. Primary Control Board

This board acts as a platform through which the micro-controller, Arduino Mega 2560 controls the motion of the vehicle by manipulating the thruster RPM using dedicated motor controllers for each thruster, as per the commands directed from the main computer. It also facilitates the actuation of the pneumatic sub-system to trigger the torpedo and marker mechanisms. The board interfaces with various sensors used on the vehicle. Use of surface mount devices has provided a compact layout.

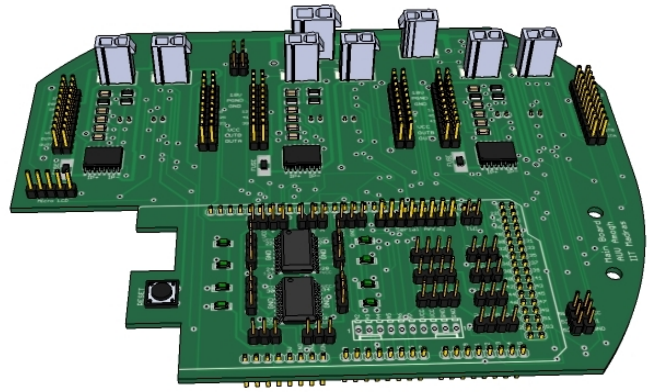

Fig. 18. Primary Control Board

D. Motor Driver

A Motor Controller board based on ST Microelectronics VNH5019A-E has been designed to drive the propulsion system of Amogh. It can take a wide voltage supply range of 6 V-30 V, supported with peak current of 30 A and continuous output current of 12 A at a maximum PWM frequency of 20 KHz. It consists of on-board short circuit, over heating, and under voltage protection peripherals.

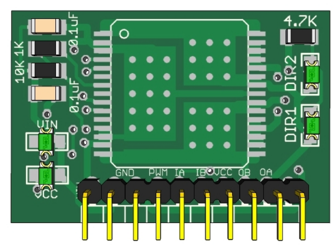

Fig. 19. Motor Driver

E. Power Management System

The power management system of Amogh has been designed for an endurance of 45 minutes at maximum continuous load. The required current capacity of 32 AHr is obtained from four Lithium-Polymer (Li-Po) batteries. The thrusters are powered through two 5S Li-Po batteries in parallel whereas two 3S batteries in parallel have been used to power all the other necessary electrical peripherals. The current and voltage across batteries, thrusters and other electrical peripherals are regularly monitored through adequate sensors and the data is logged for further analysis. This data is used to monitor and analyze the performance, health of various peripherals on the vehicle and use the results to develop an efficient power management system. All data sampled by the micro-controller is transmitted over a serial link to the motherboard hard disk.

F. Power Board

Component	Avg. Working Voltage	Avg. working Current	Quantity	Total Power Requirements
Thrusters	18.5	3	6	333 W
Computing Unit	12	8	1	96 W

Other than the thrusters, the major power consuming unit is the motherboard with CPU. All the remaining sensors and devices have significantly low power consumption. The power distribution board sources, regulates and distributes power to various devices. The board implements current/voltage monitoring, under voltage protection and magnetic reed switch based trigger.

Fig. 20. Power Board

G. Sensors

The sensor payload on Amogh comprises of the following:

- Pressure Sensor
  Amogh uses a resistive analog pressure transducer. A strain gauge attached inside to the diaphragm on the water side of the transducer measures changes in the resistance on the application of external pressure. This change is calibrated to monitor depth.

Fig. 21. Pressure Sensor

- Inertial Measurement Unit (IMU)
  The IMU in Amogh is VN-100 rugged by Vector-NAV. Its a miniature, high performance IMU with the attitude and heading reference system. This is capable of providing drift free high accuracy orientation output and maintains the heading. It combines 3-axis accelerometer, 3-axis gyroscope and a 3- axis magnetometer with a 32-bit processor.

Fig. 22. IMU

- Cameras
  The AUV uses a Logitech B910 HD web camera, it is capable of capturing video feed with 720p resolution. It also supports a video resolution of 640×480 capture which is optimum for image processing and has a USB 2.0 interface for transferring the video feed. It provides a 78-degree field of view. The camera provides a consistent frame rate of 30 fps.

Fig. 23. Logitech B910 Webcam

- Current Sensor
  Amogh uses Hall effect current sensors across the thrusters, batteries and the motherboard. They help us to keep a track on the amount a current flowing through each device.
- Voltage Sensor
  A simple voltage divider circuit has been be used as voltage sensor to regularly monitor the voltage of the batteries and provide feedback to the microcontroller.
- Leak Detection Sensor
  A leak detection circuit is employed to detect if water accidentally seeps into the hull. Two circular probes mounted near the end cap of the hull monitor the intrusion of water inside. The feedback obtained in terms of voltage due to the conductivity of water is amplified and is provided as an input to the micro-controller.

H. Feedback

The feedback from the sensors through a multiplex channel via micro-controller reaches the main on-board computer over a serial line where it is stored in the system hard disk. The data stored is used after the mission, to monitor the system characteristics and for debugging purposes.

I. Thrusters

The AUV is propelled using BTD 150 thrusters from Seabotix. The thrusters run on 19.1 V DC supply, consuming maximum continuous current of 4.25 A and peak current up to 5.8 A. They provide two blade bollard thrust of 2.2 to 2.9 kgf, helping in manoeuvring the vehicle through obstacles. A Saddle mount is used to mount thrusters on the hull, the saddle made from aluminium serves as a frame, protecting the thruster and securing it to the hull.

Fig. 24. Seabotix BTD 150 Thruster

J. Electronics Enclosure

The circuit boards have been stacked in a compact fashion inside the top hull which has provided an appreciable space advantage as compared to the previous version.

IV. IMAGE PROCESSING SUB-SYSTEM

Image processing is the use of algorithms for processing images from a camera. The AUVs sight comes from the two cameras - front-facing and bottom-facing - present in it and the image processing algorithms that make sense of the data captured from the cameras. The raw video stream from the camera is processed in two phases.

In the first phase, images are preprocessed to enhance color and brightness. This is required to compensate for the effect of the photo being captured underwater. Images taken underwater have a blue tinge and have lesser intensities on the red channel than the actual observed colors. Attenuation of light is also a common issue underwater, leading to darker images and reduced visibility.

In the second phase, the enhanced images are processed by algorithms that understand the contents of the image in order to identify the objects around the camera. This is a high-level processing step that directs the navigation of the AUV. Such algorithms include modules such as object detection and pattern matching.

OpenCV, an open source computer vision library was used for implementing the algorithms. An overview of the approach is shown in the Fig 25.

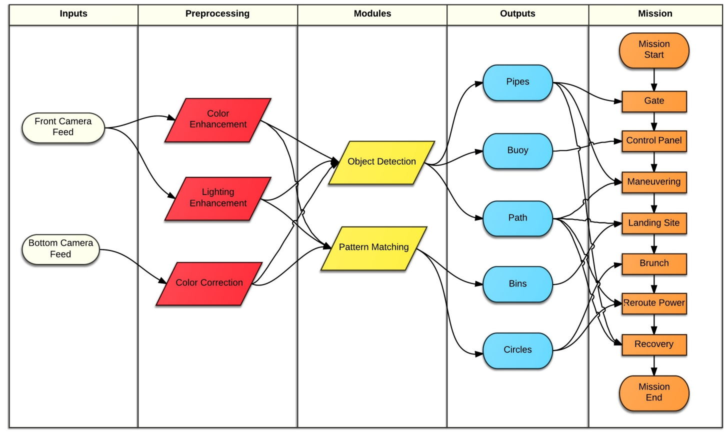

Fig. 25. Control flow Summary

Image Enhancement

Images taken underwater are subject to light attenuation and a bias in the color spectrum towards the blue band. Enhancing the images to correct the brightness and contrast will help subsequent processing steps. In this section, we outline the image enhancement methods used.

Cross-channel Mixing

An analysis of the RGB histogram of images taken underwater shows a greater proportion of pixels on the blue scale and a very small fraction on the red. In this method, we compose the output image by mixing different proportions of the R, G and B channels of the input image to compensate for the blue tinge. An example of the same is shown in Fig 26

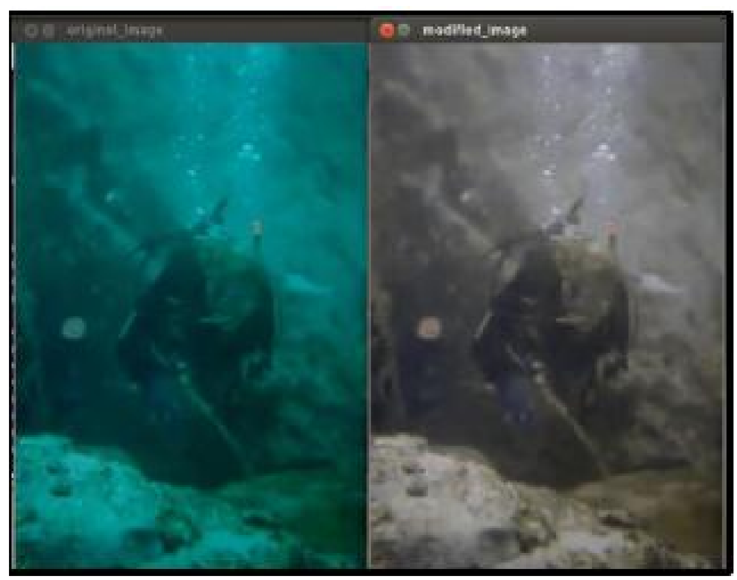

Fig. 26. Cross channel mixing

Contrast Enhancement

An effect of light attenuation and blue tinge is that the contrast between various colors captured underwater reduces significantly. This affects the detection of various objects. An example of the same can be seen in fig 27

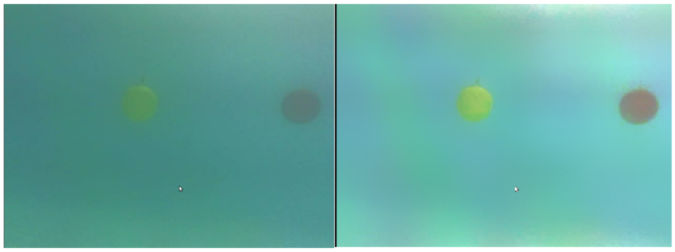

Fig. 27. Contrast Enhancement

Brightness Correction

An automatic brightness correction algorithm, based on gamma correction, was implemented. This helps subsequent image understanding and object detection steps to be fairly invariant of the lighting conditions.

Object Detection

After the image is corrected for color and brightness, the required objects are detected in two stages. The first stage involves segmentation based on color. The second stage would require the application of geometrical constraints on the segmented regions to isolate the target object based on the expected shape. (Fig 28)

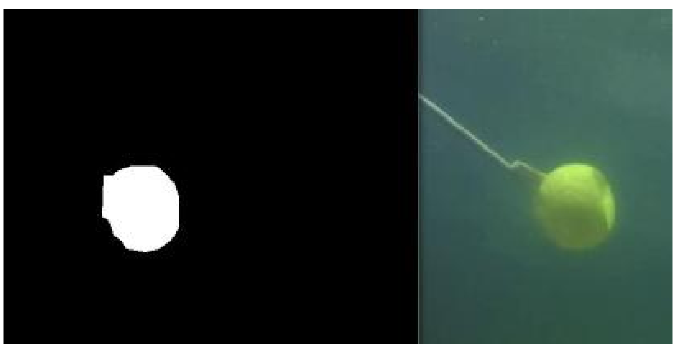

Fig. 28. Buoy detection

Pattern Matching

Certain tasks depend on the detection of patterns as well as distinguishing them from other patterns of similar nature based on their appearance characteristics.

The adopted method for pattern matching is centred on the idea of scale and rotation invariant template matching. This approach is justified by the fact that the target objects are rigid and the only transformations of them that will be observed in the captured images would be due to the camera perspective.

The proposed template matching algorithm uses intensity gradient based feature detection and comparison with a learnt set of features for the target pattern.

Acknowledgment

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