Design and Development of Autonomous Underwater System

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Abstract

This report presents a concise description of the design and development of an autonomous underwater vehicle (AUV) mainly focusing on project *Varun*, an AUV developed by the AUV-IITK team in the institute. The work shown as a part of the undergraduate project were initiated with the entire project's inception in 2014. These mainly include designing of waterproof enclosures and pneumatic system of the robot, and the power distribution board present used it the robot.

Keywords: AUV, design, enclosures, power board, pneumatics

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Acknowledgement

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I would also like to thank my fellow teammates who have become like a family for me- Shibhansh Dohare, Shikher Verma and Jayant Agarwal. They helped AUV maintain its pursuit to particpate at the national event even when times were bleak and the team had only four people including me. It is through them that I learned how important it is to collaborate on ideas and develop the right skills to interact with people. Most of it has been trial and error until we develpoed the right attitude. As said by Hellen Keller, it is true that "Alone we can do so little, together we can do so much."

I must also not forget the people with whom I worked closely on most of the projects mentioned in this report. Rithvik Patibandla, Manish Kumar, Akash Jain, Harshvardhan and many others have all been truly innovative in the ideas they have putforth, and it has been great to work together with such minds. The amalgation of unique characteristics of each of them has had a mark on the project in its own way.

Remembering the times I used to be so engrossed at my work that I didn't get time to talk to my friends or family members for most of the week; I would also like to express my appreciation for their understanding of my absence from their life during those times. It would have been tough had they constantly tried to make me sleep or rest rather than work on the project after my classes.

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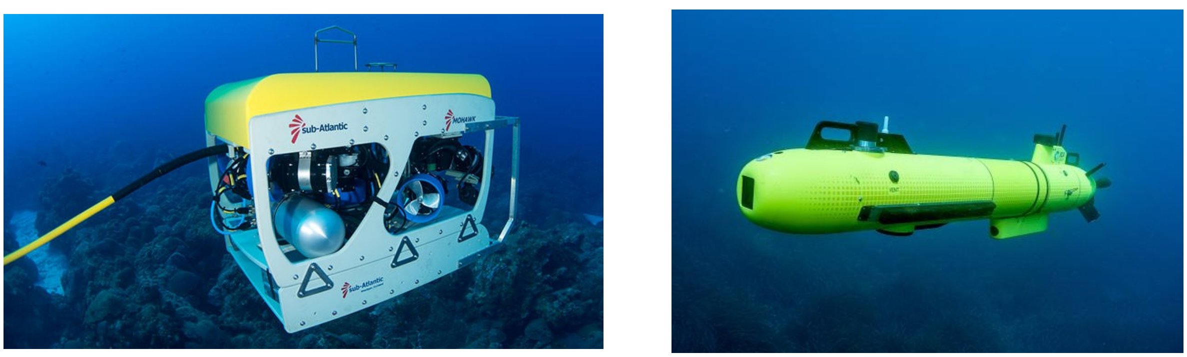
1. Introduction

1.1. Unmanned Undersea Vehicles

The unmanned undersea vehicles (UUVs) are being used for oceanography since the 1950s-60s. However, the potential of these self- propelled vehicles extended to a wider set of applications under military tasks as classified by the Navy forces of various countries. In present, UUVs are categorized into two broad classes (a) Autonomous Underwater Vehicle (AUV), and (b) Remotely Operated Vehicle (ROV).

AUVs are unoccupied submersibles without tethers which are powered using on- board batteries, fuel cells, or other energy resources. They are intended to carry out programmed missions with little or no direct human intervention, and may communicate with operators intermittently using acoustic links, satellite communication (SATCOM) systems.

ROVs, on the other hand, are unoccupied, tethered vehicles with cables to carry power, sensor data and control commands from an operator on the surface. They have nearly unlimited endurance but their maneuverability is limited to the tethers' lengths.



(a) Remotely Operated Vehicle (ROV Mohawk by NOAA)

(b) Autonomous Underwater Vehicle (Project SWARM by ECA)

Figure 1: Two Broad Categories of UUVs

As given in [2], UUVs are typically associated with the following categories of missions:-

1. **Intelligence, Surveillance, and Reconnaissance (ISR):** Under this, the UUVs are supposed to perform exploration into inaccessible or contented waters using mast-mounted sensors. This mainly involve tasks like specialized mapping, localization, object detection and near- land monitoring.

2. **Mine Countermeasures (MCM):** In MCM, the UUV establishes safe operating areas, transit routes and lanes. The expected operation duration is typically 7- 10 days, and the area of interest spans the water column ranging from deep mines waters

to on- beach support. The MCM functions are best suited for mine hunting and mine neutralization. The key metrics for this kind of mission is to maximize area coverage rate and minimize the time spent in conducting the mission.

3. **Anti- Submarine Warfare (ASW):** The main objective of ASW is weapon engagement. This has to be done under certain rules of engagements, without accidentally raising a conflict. Generally UUVs are deployed before manned vehicles arrive in the operating area to carry out the submarine operations. For ASW operation, the UUV must clear and maintain a carrier strike group operating in area free of threat submarines and also plan routes for safe routes in the territory.

4. **Inspection/ Identification:** These support homeland defense and protection needs such as inspection of ship hulls, and repair of underwater pipes. These kind of missions are often carried out by divers. However, factors like poor visibility, tending- line entanglement, hazardous conditions (such as confined space) pose risks to the safety of the divers. To solve this, several ROVs and AUVs have been successfully deployed to carry out such tasks.

5. **Oceanography:** UUVs may also be used to collect oceanographic data like ocean-current profiles, temperature pr ofiles, salinity profiles and bioluminescence. These operations can be done through optical imaging, bathymetry, acoustic imaging, and bottom mapping. Oceanography and MMC missions often overlap in nature.

6. **Communication/ Navigation Network Node (CN3):** CN3 missions include communication functions like acting as a photo booth, and navigation functions like deploying transponder and providing inverted (antenna-to-surface) GPS capability to access navigation data without required the UUV to come to the surface.

7. **Payload Delivery:** Typically meant for large UUVs, payload to be delivered may vary from cargo to MCM neutralization devices to weapons for deployment or pre-positioning.

8. **Submarine Search and Rescue (SSAR):** Missions like these include recovering bodies, evidence, and flight data recorders. Using UUVs for SSAR operations are attractive in certain environmental conditions like under ice on frozen lakes, or in highly polluted rivers.

From the list of missions advocated above, a few of these missions can be accomplished better by an AUV than by a manned vehicle or ROV. In general, there are a wide range of tasks for which an AUV is said to be either a formidable or the only choice available due to factors like cost and safety. Elimination of tether in an AUV, frees the vehicle from the surface vessel and eliminates the large expenditure which might have occurred for handling gear that a tether requires. However, the difficulty in through-water imposes the requirement that an AUV is able to function safely and productively without supervisions.

1.2. AUV and its Components

The major modules/ components present in an AUV can be listed as shown in Table 1.

Component	Description
Pressure Hull	Pressure hulls help withstand sea pressure as AUV descends into the ocean. The pressure to which an AUV is subjected increases linearly with depth. Small hulls are able to withstand pressure than are large hulls (such as in submarines).
Ballast Systems	Ballasting enables AUVs to operate at neutral or near-neutral buoyancy such that the hull is nearly horizontal when submerged. Fixed-buoyancy systems that use lead or foam are engineered into the AUV and adjusted as changes to vehicle components or payloads occur.
Masts	Masts support AUVs' electromagnetic sensors (including optical sensors) and any navigation (i.e., GPS) antennas. Mast enclosures effects the designing of vehicle pressure hulls as they need to withstand ambient pressure down to a vehicleś intended maximum operating depth.
Power and Energy	Power available to a UUV determines how fast it can go, while energy determines how far it can go. Recently, vehicles use lithium polymer batteries that have high energy density and are rechargeable.
Electrical-Power Distribution	Electrical power is distributed in AUVs using a bus system having devices to ensure uniform battery drain and to handle ground faults.
Propulsion	Propulsion is generally provided by an electric motor that turns a propeller. Brushless direct-current (DC) motors for propulsion boast several advantages over brushed motors, in the areas of efficiency, reliability, and power density.
Navigation and Positioning	GPS signals are attenuated by seawater. The AUV then uses an internal navigation system, such as an inertial guidance system that measures and integrates acceleration or a Doppler Velocity Log system that uses sound to measure velocity along and across the vehicle's track relative to the sea or relative to the bottom.
Communication Systems	Communications are needed once a vehicle has been launched and tested to initiate a mission. The ability of AUVs to communicate while submerged is limited by physics. Acoustic communication system is commonly used, although they provide low data rates, and can drain significant amount of power.
Maneuvering Systems	UUV maneuvers are generally controlled by using thrusters or vectored propulsions. Multiple thrusters allows the vehicle to perform differential turning, move vertically or even laterally.

Table 1: Components in an AUV

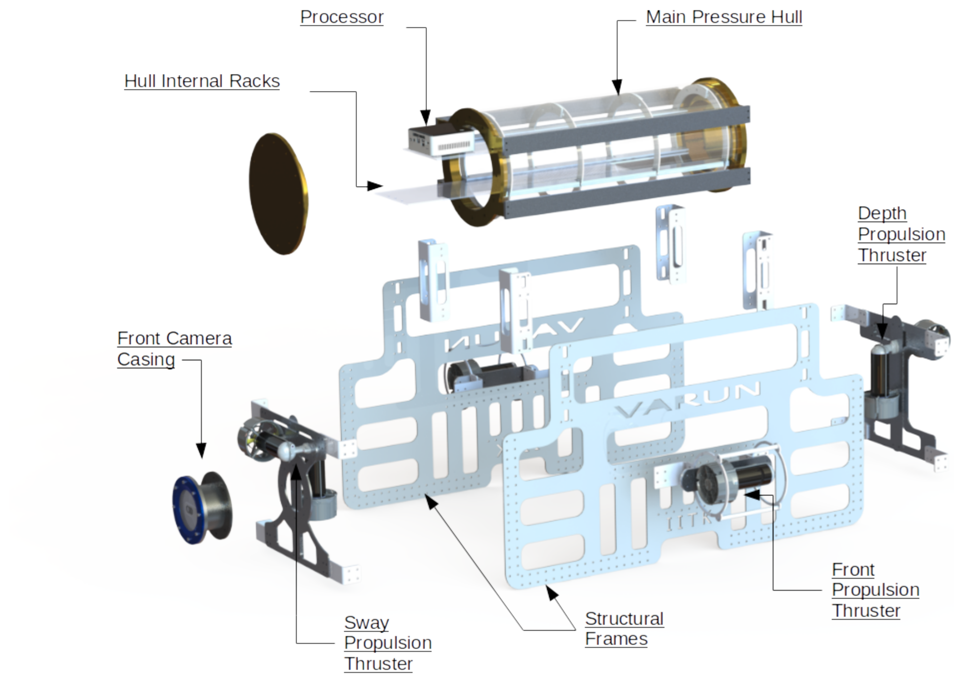


Figure 2: Overview of Components present in *Varun*

Sensor	Description
Inertial Measurement Unit (IMU)	Comprises of Gyroscope which measures angular rates and accelerometer which measures the force required to accelerate a proof mass. The two (along with magnetometer) helps in estimating the vehicle's orientation, and velocity, however are plagued by drift and biasing errors.
Compass	It provides a globally bounded heading reference by measuring the magnetic field vector. It is subject to bias in the presence of objects with strong magnetic signature
Pressure Sensor	Used to measure underwater depth. It can attain high accuracy as pressure gradient is steeper underwater.
Doppler Velocity Log (DVL)	Uses acoustic measurements (Doppler effect) to capture bottom tracking in order to determining the AUV's velocity vector (heave, surge and sway) relative to the sea-floor. DVL consists of typically 4 beams.

Table 2: Dead-Reckoning Sensors for an AUV [4]

1.3. Problem Statement

"To develop an autonomous underwater vehicle capable to navigate autonomously underwater and perform tasks like shoot torpedoes and drop markers"

Project *Varun* from AUV-IITK group is intended for ASW and inspection application. However, the above problem has a variety of dimensions to it which can be divided into mechanical, electrical and software subsystems. To work on all the parts of such a big project is not an individual's job, and requires a good team to work in unison towards a goal.

As a part of an undergraduate project, the following are the key contributions to the development of project *Varun* that have been described in this report:

1. Designing and manufacturing of various mechanical parts and assemblies
2. Simulation and Fabrication of the power distribution board

1.4. Motivation

India has a coastline of length 7,516.6 km (4,670.6 mi). According to the United Nations Convention on the Law of the Sea, a country can claim up to 12 nautical miles from its coast as territorial water and up to 300 nautical miles from its coast as Exclusive Economic Zone (EEZ), where it can carry out activities for commercial use. The ability to exploit the oceans' resources and minerals, along with securing the waters can help strengthen the country's economy and naval defenses. However, instead of importing marine technologies from other nations, developing AUVs and its components indigenously for this purpose is a strong motivation to carry out research in designing of these systems.

As mentioned earlier, marine autonomous systems have the ability to revolutionize our current abilities to map and monitor the marine environment. Even though these vehicles promise a strong potential in defense, industry and policy sectors, the amount of research occurring in this field is lower in comparison to other autonomous systems such as unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs). The reasons for AUVs to still be in their nascent stages of development might be due to a severity of the challenges that are present and the massive amount of resources required to attract researchers towards this field.

One way to attract people towards AUVs is to target the promising youth of the country to get acquainted with this field early in their career. Providing the problem to build underwater systems to engineering students, who have limited access to resources and funding, has a two-fold benefits. It provides them a platform to think about low-cost solutions to the challenges of an AUV, and trains them towards what engineers are known to do the best-bringing ideas into existence. Working on such big projects for a prolonged periods gears them towards real-world scenarios and issues that are frequent in nature while working in a research group.

To encourage above, the National Institute for Oceanic Technology (NIOT) and Defense and Research Development Organization (DRDO) in the country organize events and conferences where the students and research scientists in the country get to interact and compete friendly towards pushing the AUV technology to greater heights. The competition NIOT-SAVe 2017 required AUVs to perform tasks like follow lines underwater, shoot torpedoes on specific targets, drop markers into bins. These are a simplification of a larger set of problems on which research for AUVs are occurring.

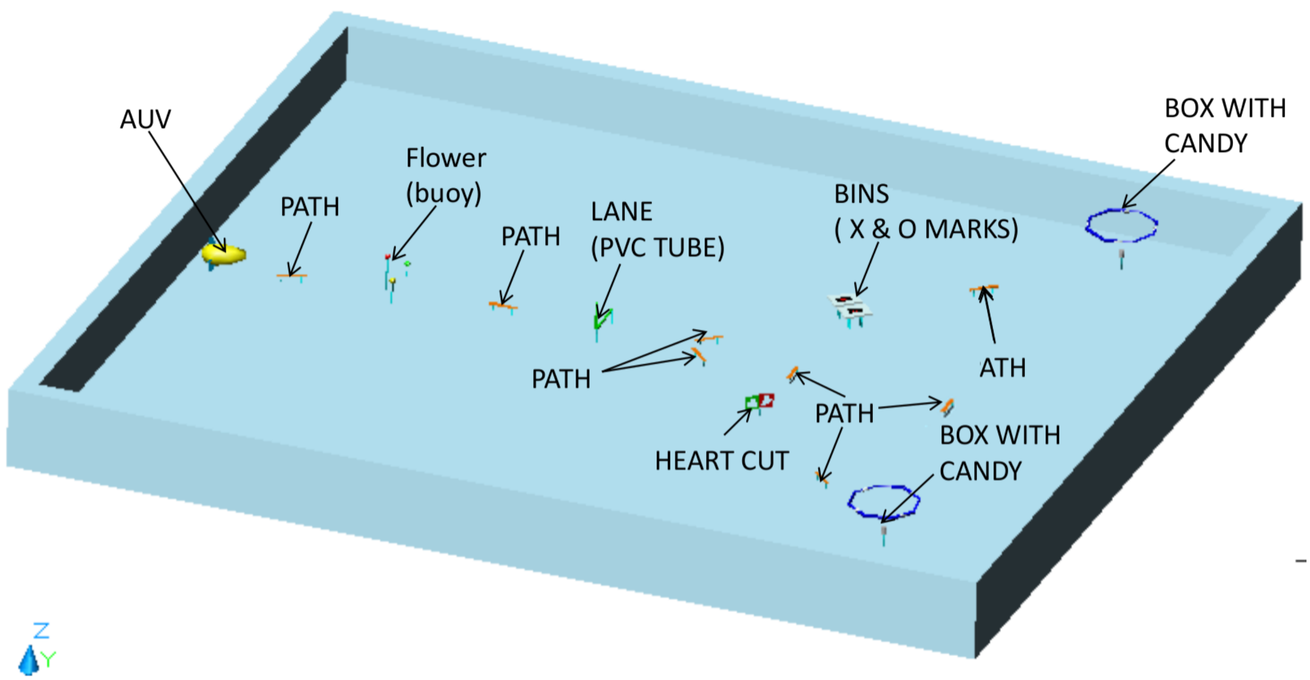
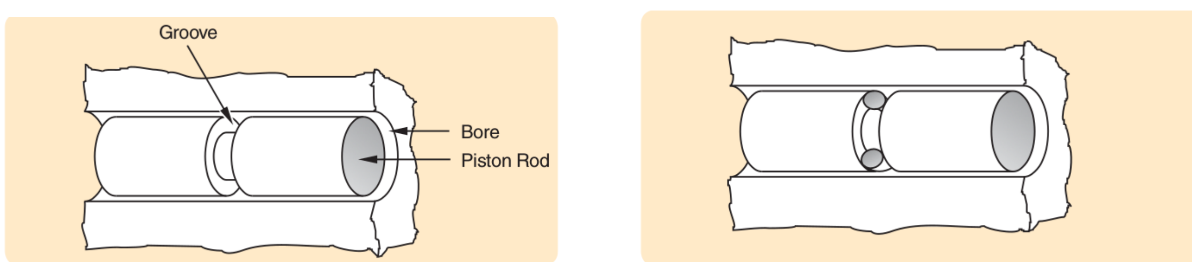


Figure 3: Arena for the NIOT-SAVe Competition 2017

2. Mechanical Aspects

2.1. Waterproof Enclosures

Compared to other robotic systems, in UUVs we need to seal the robot enclosures for protection against water. The recommended *ingress* protection is referred to IP68 or above for all the enclosures. Failure to meet this requirement would lead to damaging of the electronics which is undesirable. For waterproof sealing the most reliable method is using O- rings. An O-ring is a torus, or doughnut-shaped ring, generally molded from an elastomer, and is used to prevent loss of a fluid or gas. Although available in a variety of materials, then one we have used in our robot are made of neoprene rubber. In our robot, O- rings have been used in two different ways: face seal and bore seal. An important design factor which comes into picture while using O-rings is the size of the groove that needs to be made to have a nearly perfect sealing. The size of the O- ring groove for seal is listed in Parker's O-ring Handbook [1] pages 4-10 to 4-25. As a cautionary step before adding O-ring to seal it is essential to ensure that the gland has a surface finish of Level 1, i.e. the dimensional variations are within tolerance bad.



(a) Basic Gland

(b) Gland and O-ring

Figure 4: A typical static bore seal where O-rings are used *(Source: [1])*

2.1.1. Main Pressure Hull

The main pressure hull of the robot encloses the main circuitry of the robot. This includes the power distribution board, the power supplies (batteries), the processor and controller, the battery monitoring board, and sensors like the inertial measurement unit (IMU) and depth sensor. In order to accommodate these many electronics it is required that the pressure hull is a bit large in size. It is important to decide the space the electronics require as increasing the hull size increases the buoyancy of the robot, a parameter which later needs to be balanced out.

There are a variety of choices for the shape of the pressure hull, however, we chose it to be cylindrical as it is easy to seal and the drag coefficient is lesser for cylindrical than for a cubical box. This has been verified by us using Ansys Fluent toolbox.

The cylindrical hull can be decomposed into three parts: the tube, the flange and the cap. The tube has been made out of acrylic which is transparent in nature, making it easy to view the battery monitoring board and perform a caution to check for leakages in the hull. The flanges and cap, made out of aluminum T-6 alloy, have been designed using computer aided designing tool Autodesk Inventor. The two parts have been manufactured using Computer Numeric Control (CNC) lathe and milling machines. A detailed design of the main pressure hull's flange is shown in Figure 5.

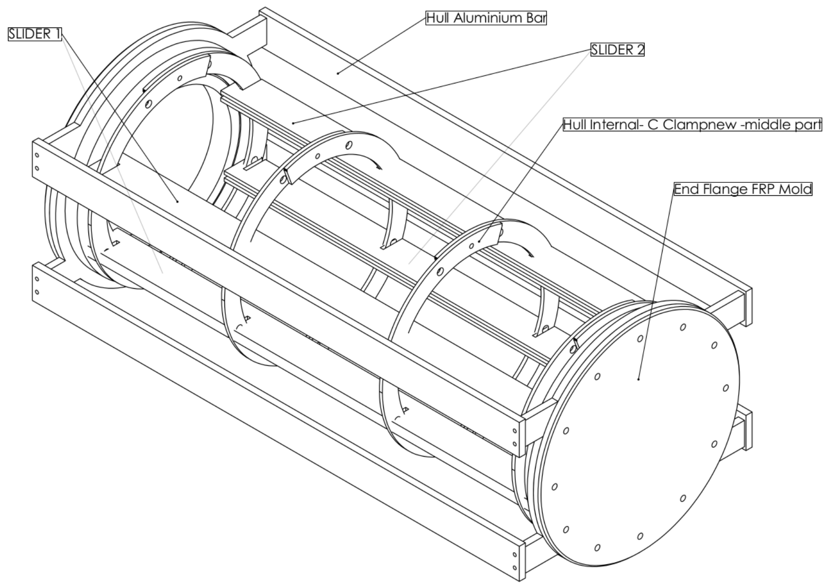


Figure 5: Main Pressure Hull

2.1.2. Camera Enclosure

As the name suggests the camera enclosures are meant to protect the camera from moisture. The camera being used in *Varun* is Logitech C930 webcam which has dimensions around 29 mm x 94 mm x 24 mm. The camera provides a field of view of 90^o. It is to be ensured that the field of view is not obstructed due to the enclosure for best possible use.

In comparison to the pressure hull, for the camera enclosure only a face seal proves to be sufficient for a tight seal. The enclosure has been made out of aluminum T-6 alloy body with an acrylic lid on top. Instead of manufacturing the entire enclosure using CNC, various parts of it were first manufactured using abrasive water-jet cutting (WJT) and using conventional lathe machine; after that they were welded together using tungsten-inert-gas (TIG) welding.

To screw the lid over the aluminum body, we used M4 allen screws made of stainless steel for fastening. A total of eight screws are required to ensure uniform force across the lid, thus pressing the o-ring tightly. A detailed design of the camera enclosure can be seen in Figure 6.

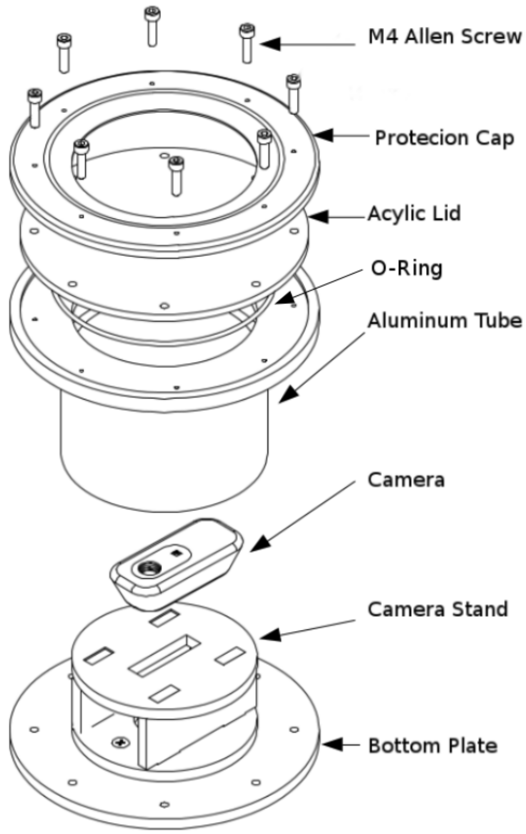


Figure 6: Camera Enclosure

2.2. Pneumatic Systems

Pneumatic systems are operated by air/gas in pressure. A simple pneumatic system being used in *Varun* comprises of the following:

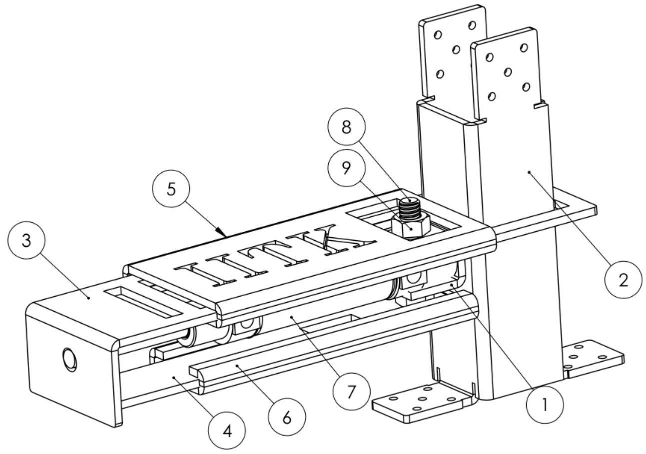
1. **Pneumatic Reservoir:** 100 bar Tiberius Guerilla paintball tank provides the storage unit of the compressed air which serves as the air supply for the entire system.

2. **Supply:** Supply consists of feed lines which are used for transportation of air throughout the system with valves in between to control the flow. Solenoid valves are easy to trigger using signals sent from the micro-controller and are commonly used.

3. **Cylinders:** For marker dropping task, a double acting pneumatic cylinder has been used.

2.2.1. Marker Dropper

An earlier prototype for the marker dropper required two double acting cylinders to drop two markers when actuated. However, to reduce the weight of the entire system, a constraint of single cylinder was imposed and design changes were made accordingly. With slight modifications, a marker dropper capable of dropping spherical balls of diameter 50 mm was made. The assembly of the marker dropper, made out of aluminum T-6 alloy, is shown in Figure 7. The manufacturing involved processes like abrasive WJT, milling and welding to assemble the parts.



ITEM NO.	PART NUMBER	QTY.
1	clamp	1
2	Main Body	1
3	Plate 1	1
4	Plate 2	1
5	Slider 1	1
6	Slide 2	1
7	Pneumatic Cylinder	1
8	Bolt	1
9	Nut	1

Figure 7: Marker Dropper Assembly

2.2.2. Torpedo Shooting Assembly

As shown in Figure 8, the assembly contains of three parts: the non- return valve, the torpedo holder and the polycarbonate tube. The torpedo shooter uses a non-return valve which is normally closed, that is the valve allows only a uni-directional flow of fluids across the membrane. The valve opens only when the highly pressurized air flows through the feed line connected to the valve, thus preventing water from entering the pneumatic system.

(a) Designed Assembly **(b)** Manufactured Assembly

Figure 8: Torpedo Shooter Assembly for a single Torpedo

3. Electrical Aspects

3.1. Power Distribution

The vehicle is powered using Lithium-Polymer (LiPo) batteries of 3S 11.1V, 5000mAh each. However, not all electronics being used in the robot operate at 11.1 volts. A schematic overview of the power distribution requirements for *Varun* is shown in Figure 9.

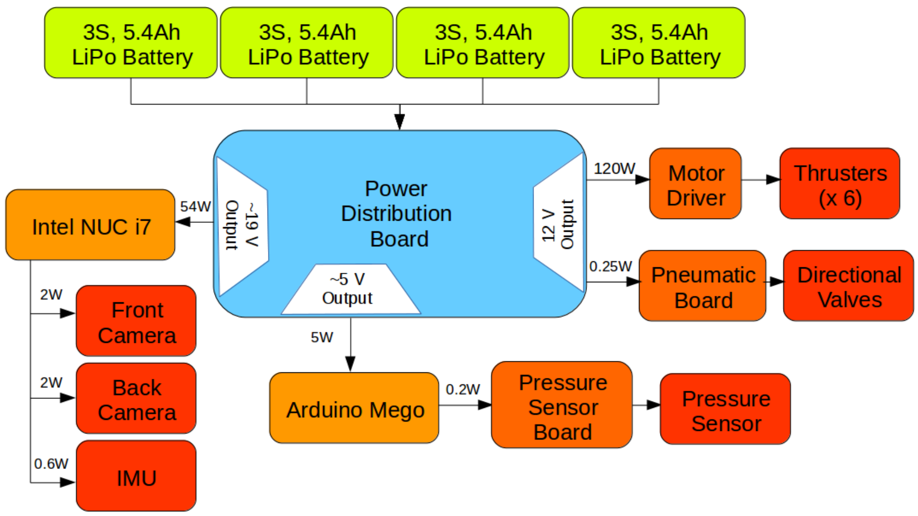


Figure 9: Power Distribution on *Varun*

One of the few initial attempts to power the robot was done using the board shown in Figure 10. It used two LiPo batteries: one 2S and other 3S with 2000mAh each. At that time the robot was using the processor Odroid U3+ which requires lesser power compared to the later used Intel NUC.

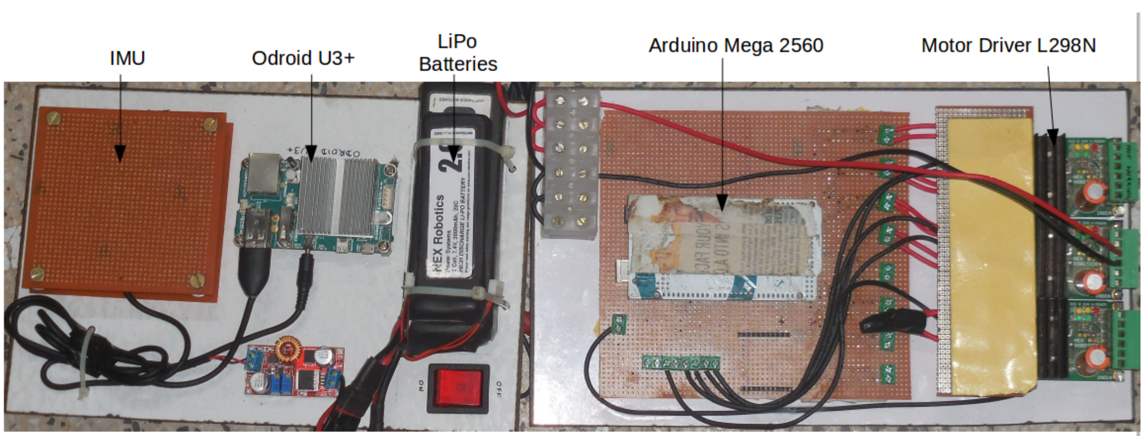


Figure 10: Prototype Board made for *Varun* with Odroid Processor and IMU

The final board with power distribution as described in Figure 9 is shown in Figure 11.

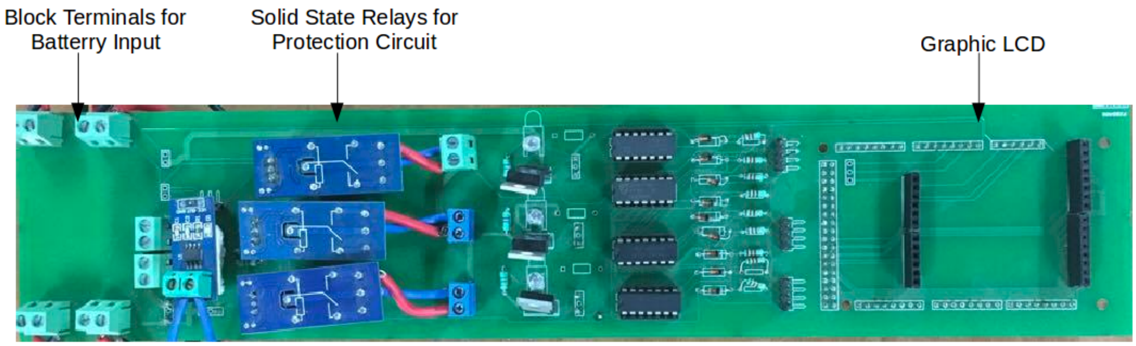
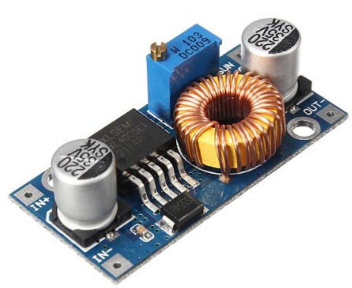


Figure 11: Final Printed Circuit Board made for *Varun* (Top View)

To manage the power requirements, the power distribution board creates power lines that operate at different voltage levels. This is achieved using step-down and step-up switching regulators which are also known as buck and boost converter respectively [3]. The buck converters used in the project are XL4005 modules, that are operated at 18kHz and have a conversion efficiency of 96%. The buck converters are capable to provide output currents up to 4.5A and can admit input from a range of 4V-38V. The boost converter modules on the other hand, are based on popular Texas Instrumentś UC3844 current mode PWM controller chip which converts an input of 10V-32V to 12V-35V at an efficiency of 94%. This is sufficient to power our on-board processing unit, Intel NUC i7, which is operated at 19V.



(a) XL4005 Buck Converter Module

(b) UC3844 Boost Converter Module

Figure 12: DC to DC Converters

3.2. Protection Strategies

3.2.1. Voltage Protection

The biggest limitation of LiPo batteries is their voltage sensitivity. A typical LiPo cell in working condition has a lower limit on voltage at around 3V and a upper limit at around 4.2V. Care should be taken to ensure that the voltage of the cell doesnâĂŹt go below 3V while continuous usage. Moreover, while charging the batteries, it is required to ensure that the voltage doesn't exceed 4.2V. Since the LiPo battery charger (provided by Turnigy) takes care of the over-voltage limitation, we only only implement under-voltage protection. This is achieved using op-amp as a comparator with zener diodes as a voltage reference. Since there are three cells in the 11.1V LiPo battery, we have used 3 op-amps and the output of the op-amps are connected to a 3-input AND gate and the output of the gate is connected to a relay. The circuit, shown in Figure 13 works the following way: When the voltage of a cell falls below the reference voltage, the op-amp output becomes a low thus making the output of the AND gate low. This turns off the relay and disconnects the battery from the remaining circuit before any severe damage may occur.

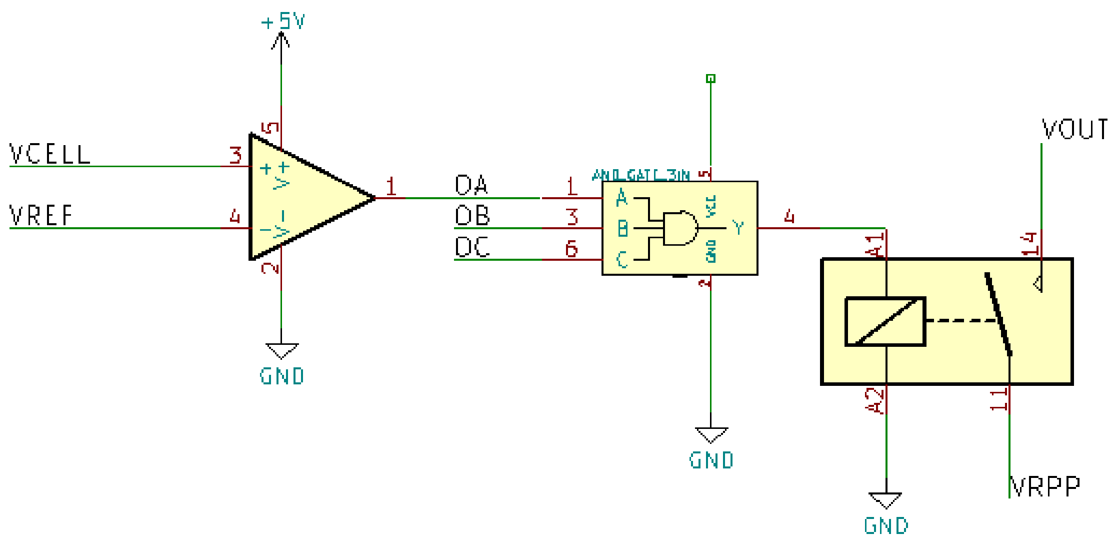
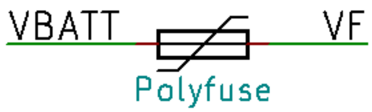


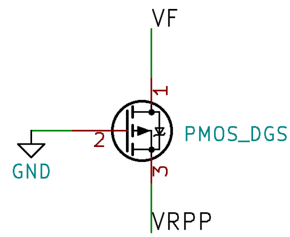
Figure 13: Schematic Diagram of the circuit for Voltage Protection

3.2.2. Over Current and Short Circuit Protection

Another limitation of the LiPo battery is its maximum discharge rate. Though the current rating of the LiPo batteries we used is 100A, the batteries wonâĂŹt be able to sustain a short circuit discharge. Since, the current ratings of all the components are known, a current discharge value that is much more than expected value indicates damaged components and/or incorrect circuitry. Over current protection is achieved by using a re-settable fuse. The fuse works on the principle of heating. When the current in the circuit increases more than the specified value, the fuse gets hot and the resistance of the fuse increases thus decreasing the current. When the source of over current is taken off, the fuse cools down and acts as a very small resistance in series with the battery.



(a) Schematic Diagram of the circuit for Over-current Protection



(b) Schematic Diagram of the circuit for Reverse Polarity Protection

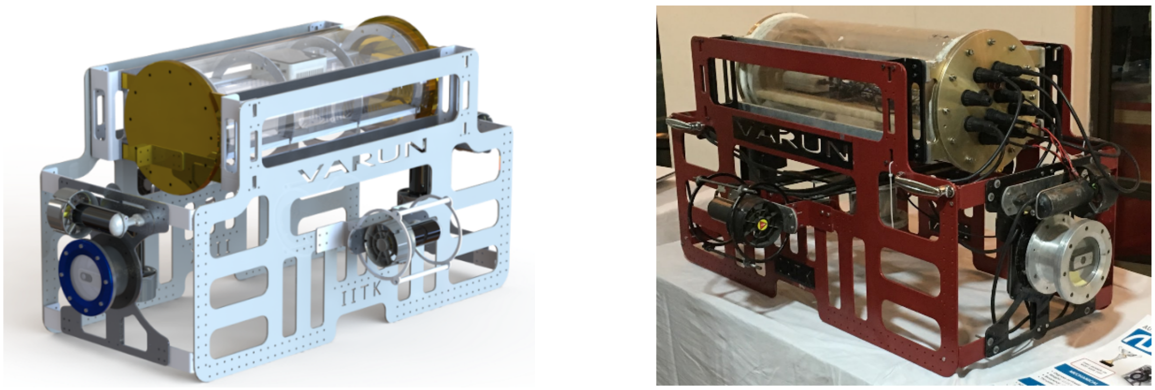
Figure 14: Protection Circuits

3.2.3. Reverse Polarity Protection

The batteries are often taken out off the vehicle (for instance, for charging) and then need to be reconnected. There is a chance of connecting the batteries in reverse order of their polarity by mistake. This might lead to damage of the on-board components. To save the circuit from this type of situation, reverse polarity protection circuit is added. A P-Channel MOSFET(PFET) is used for this purpose. The PFET acts as a short circuit when the battery is connected properly and this lights up an indicator LED. When the battery is connected in reverse, the PFET acts as an open connection thus saving the rest of the board.

4. Conclusion

The first year run of AUV-IITK focused on building a prototype of an underwater vehicle. Although naive compared to existing AUVs, its successful development has become an important mark for the team. It has helped in verifying the reliability of the initial setups for experiments and the tests that were carried out.



(a) Rendered Model of the AUV *Varun*

(b) Fabricated AUV *Varun*

Figure 15: Rendered and Fabricated Models of AUV *Varun*

The robot after going through rigorous testing underwater for a period of two months performed at the NIOT-SAVe 2017 in December 2016, where it stood second in the team's debut at the event. The feat help establish that the the team met the promised deliverables worked effectively under the monetary constraints .

Table 3: Design Aspects of *Varun*

Feature	Value
Degrees of Freedom	5
Number of Thrusters	6
Dimensions (in mm)	$1081 \times 434 \times 530$
Weight	39.550 kg
Buoyancy	+2% of weight
Depth of Operation	20 m
Battery Life	>2.5 hours
Coefficient of Drag (at velocity 1 m/s)	
Translation	0.29
Downwards	0.25
Sideways	0.21

Table 4: Monetary Funding for *Varun*

Item	Cost (in $)
Thrusters (Seabotix BTD-150)	4,500
Pneumatic Assemblies and Valves	400
Waterpoof casings and hull	900
Waterproof Connectors	450
Other manufacturing components	550
Processor (Intel NUC)	400
Sensors (Pressure sensor, IMU, Cameras)	450
Li-Po Batteries (11.1 V 5000mAh)	450
PCB Manufacturing	600
Miscellaneous Electronics	150
Total:	**USD 8,850**

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