Design of a Compact ROV for River Exploration

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ABSTRACT

Remotely operated underwater vehicles (ROVs) are being extensively used in marine industry for exploration, pollution control, and military applications. With time ROVs have become smaller, less expensive, reliable and practical for small scale use. This paper presents the design of a compact low-cost ROV for river exploration with a modular structure. The ROV is neutrally buoyant which increases its efficiency. The ROV uses three thrusters for its movement inside water and has 3 degrees of freedom (DOF). A detailed 3D model is developed using SOLIDWORKS and stress analysis has been carried out to ensure it will not fail under hydrodynamic pressure. Hydrodynamic characteristics are studied using ANSYS FLUENT, which helps in determining the maximum thrust required for the vehicle propulsion and the maximum achievable velocity. The prototype is manufactured with glass fiber composite and fitted with different electronics components, sensors, and battery. The field test of the ROV is carried out in a controlled underwater environment.

CCS Concepts

• **Applied computing → Computer-aided design** • Computer systems organization → Robotic components

Keywords

Underwater vehicle; ROV; Finite element analysis; Fluid-structure interaction; Glass fiber composite.

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1 INTRODUCTION

In spite of significant improvement in technology, the vast and deep oceans remain unexplored till date. Exploration and safety of these natural resource-rich habitats led to the development of underwater robotic systems. Unmanned underwater systems have huge applications and advantages over human drivers because of the low operation cost, no human causality and ability to operate for a longer period in deeper and harsh environmental conditions. Remotely operated underwater vehicles (ROVs) are such robotic systems, which are currently being used for exploration, environmental safety monitoring, and scientific research etc. ROVs used in marine industry are highly expensive. They incur high operational and maintenance cost as skilled operators are required, a ship or boat is required for deploying these ROVs in the sea. These vehicles are heavy, bulky and equipped with advanced sensors and control systems. These can travel deeper than 5000 meters. Highly expensive and sophisticated ROVs are being developed by some organizations for specific requirements. MBARI's Ventana, Tiburon and DocRicketts [4, 5]; SUB-fighter 30K ROV by Sperre AS [2]; KAIKO Mk-IV by JAMSTEC [1] are examples of such ROVs. Some small scale ROVs are being built for educational purposes and student competitions. Over time these small scale ROVs have become more sophisticated. MARUM-Squid[3] developed in University of Bremen is such an example. This compact ROV can travel up to 2000 m depth. With the development of low-cost high-precision sensors, compact onboard computers, high-density batteries small scale ROVs are being used for small scale scientific research. Such a compact ROV is an essential tool for local educators, engineers, scientists and environmental activists. River exploration is an example of such an application.

From the early ages, human civilizations depend on the river for its survival. Rivers affect humans in many ways. ROVs can be used to explore and study these underwater environments. It can collect a variety of required information like depth, temperature, pressure, sedimentation, turbidity, dissolved oxygen data over time or along the river bed for scientific or engineering research. It can be used for 3D mapping of the river bed, tracking and monitoring aquatic animals, water pollution. Till date, low cost reliable small scale ROVs are not available in the national market. The objective of this work is to develop a compact ROV for river exploration.

This paper is organized into following sections: In section 2 system requirements and their design solutions are discussed. Design solutions involve stress and hydrodynamic analysis. The mechanical and electronic system design is presented in section

3. Section 4, discussed the first trial run and summary of the work.

2 SYSTEM DESIGN

Some key elements to consider while designing a small scale low-cost ROV is given below.

2.1 System Requirement

The basic challenge is to come up with a compact economical design while maintaining the quality and to address some practical issue in making a reliable ROV.

While designing a compact system, care should be taken to have enough space for the required components and they should be accessible. ROV body must be water tight, easy to manufacture and assemble.

A neutrally buoyant body will experience less unbalance force in the vertical direction as the weight and buoyancy will cancel each other.

The ROV will use thrusters for its propulsion. While running in rivers sometimes ROV must go upstream against the flow of the river. Thrusters should generate enough through to withstand the flow of river else the ROV will blow away.

Riverweeds can create a lot of problem in ROV operations. The ROV must be equipped with required sensors to collect the quantitative information of its surrounding. ROV must have a live video capture and transmission system and a responsive control system for its operation. The essential components required for the construction of ROV are given in Table 1.

Table 1: Required components

Components	Quantity
ROV body	-
Thrusters with electronic speed control	3
Lithium polymer battery	1
Microcontroller (Arduino)	1
On board computer (Raspberry Pi)	1
Temperature sensor	1
Pressure sensor	1
Gyroscopic sensor	1
HD camera	2
12 v relay	1
Step down buck converter	1
Powered USB Hub	1
USB TO LAN converter	2
LAN cable and connecting wire	-
Controller	1

2.2 Design Solutions

In this section, ROV is designed as per the above-mentioned requirements. The ROV uses thrusters for its underwater motion in the horizontal plane and to change depth in the vertical plane. Thrusters are the most expensive component in the setup. So, to minimize the cost and to make the ROV compact, minimum number of thrusters should be used. For the required motions a minimum of three thrusters must be used. Two are used for horizontal motion (moving forward, backward & change the direction of motion) and the third one is used for changing the height in the vertical direction. As the model, is neutrally buoyant there is no unbalanced force in the vertical direction so, only one thruster can be used for vertical motion. But, for lifting the ROV without any tilt the center of the thruster must lie on the vertical line passing through the center of gravity (C.G) of the ROV. Hence the ROV model is developed around this vertical thruster maintaining the C.G of the ROV at the center of the thruster. All the components such as a battery, a dual camera setup, a microcontroller, other two thrusters are arranged in a way to maintain the C.G of the model at the central thruster. Now considering the maximum width of the components, the hull width is decided. Riverweeds can create interference in ROV operation. To minimize the interference a closed frame structure is considered. Most of the components are placed inside a single water-tight body. Most underwater vehicles have a cylindrical body. The cylinder is considered ideal next to a sphere as it can withstand more pressure and has no stress concentration zone. As most of the internal components are rectangular, the cylinder is preferred as the hull structure compared to a sphere. But, due to the cylindrical structure lot of space on top and bottom circular portion being un-utilized (see Fig. 1). This portion gives rise to unnecessary weight and buoyancy. So, a slightly rectangular cross section is considered for the hull. As the vertical thruster will be placed at the C.G a pass through hole is required at the center. To have access to the internal components in the back and front a three-part modular structure is considered. These three sections will be joined together using screw joints with rubber gasket in-between to prevent water leakage. Using these basic parameters, a 3d model is developed using the SOLIDWORKS software (see Fig. 2). Material selection for the body of ROV is the presented in section 2.2.1.

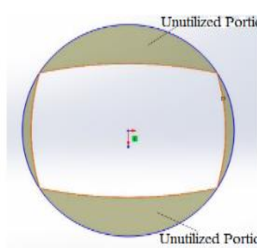

Figure 1: © Avilash Sahoo: Unutilized portion

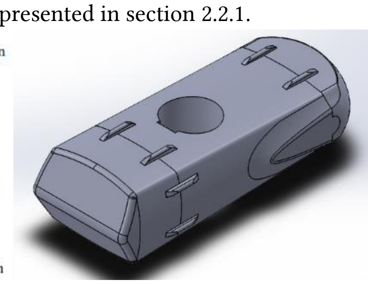

Figure 2: © Avilash Sahoo: Base ROV model

2.2.1 Material. The ROV body should be light as well as strong to withstand the underwater pressure. Fibre Reinforced Plastic (FRP) has a higher strength to weight ratio compared to materials like aluminum. Complex body structures can be easily manufactured with FRP using little professional tools, which helps in bringing the manufacturing cost and time down. FRP is a combination of a matrix medium and fibers to reinforce them. The fibers can be of glass or carbon. The fiber orientation in matrix gives directional properties to the FRP. For the robot, randomly oriented glass fibers and woven glass fiber mats are used. Due to good corrosion resistance property, glass fibers are extensively used in the marine application. FRP has high-stress resistance capability.

2.2.2 Hydrodynamic analysis. ANSYS Fluent is a computational fluid dynamic software tool for design and analysis of hydrodynamic characteristics. This tool can simulate fluid flow in a virtual environment to find flow behavior and the forces developed during the flow. In this case, the flow of water past the underwater robot is studied.

2.2.2.1 Modeling of flow field. Fluent analysis of a complex 3D model is time-consuming and requires advanced computers. Hence, to reduce the time and to get effective results the model must be simplified. In this simulation, only fluid-structure interaction at rigid solid and fluid interface is analyzed. Therefore, the internal details of the ROV are irrelevant. The holes for the screw are removed and different hollow parts are made solid and merged together to make a single solid object. As only fluid-structure interaction at rigid solid and fluid interface is analyzed, the hollow model is not required. After the modifications, the CAD model is directly imported to ANSYS Workbench from SOLIDWORKS and the model was generated in ANSYS. Then a cylindrical enclose is made surrounding the body which is the flow field for water. In this case, the solid-fluid interface is rigid and the flow of water surrounding the robot is studied. So, from the enclosure, the solid robot part is subtracted to left with the flow field only. The Boolean operation is used to subtract the body volume from the enclosure as shown in Fig. 3. Then the inlet and outlet faces are selected using the name selection option.

2.2.2.2 Meshing of flow field. Meshing quality of flow field affects the hydrodynamic analysis. For a 3D complex structure, mesh size has to be very small. But this increases computational complexity and the time consumption. Meshed flow field as shown in Fig. 4 contains 16,34,415 tetrahedral mesh elements with 2,94,592 nodes. At the solid-fluid interface mesh density in very high.

2.2.2.3 Hydrodynamic analysis of ROV. The meshed geometry is imported to ANSYS Fluent module. The material of the surrounding fluid was selected as water. In boundary condition, the inlet velocity and the Gauss presser are substituted. Drag and lift force monitors are added. In this simulation, the body was kept static and water was allowed to flow past it, which is equivalent to the ROV traveling in still water. Reynolds number is found to be greater than 10^5 considering the flow velocity from 1 to 4 m/s, the length of the model to be 0.56 m and the kinetic viscosity of water at room temperature. As the flow is turbid the standard K-Ɛ model is selected to describe the flow field. Then the solution is initialized with a reference pressure, inlet velocity and solved to get the drag and lift forces.

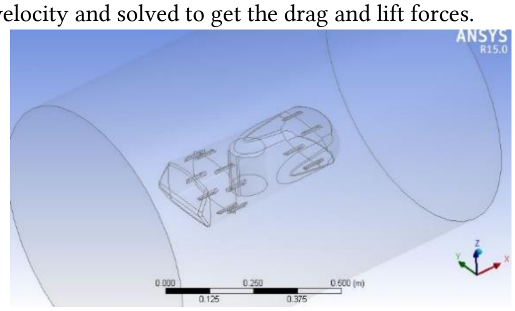

Figure 3: © Avilash Sahoo: ROV in flow field

Input and output parameters are:
Input parameters:

- Inlet velocity
- Initial gauss pressure
- Viscous Model: K-Ɛ model
- Convergence criteria: 0.00001

Output parameters:

- Maximum drag force
- Total Pressure

Figs. 5 and 6 shows the velocity and pressure contours plotted with ANSYS Fluent.

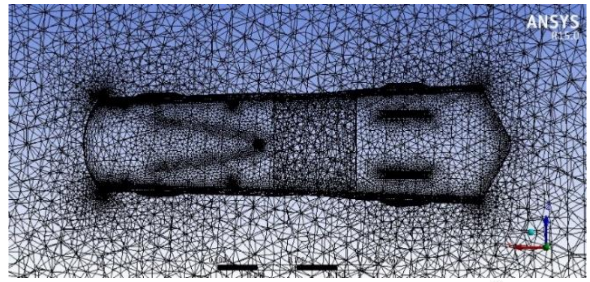

Figure 4: © Avilash Sahoo: Meshed ROV

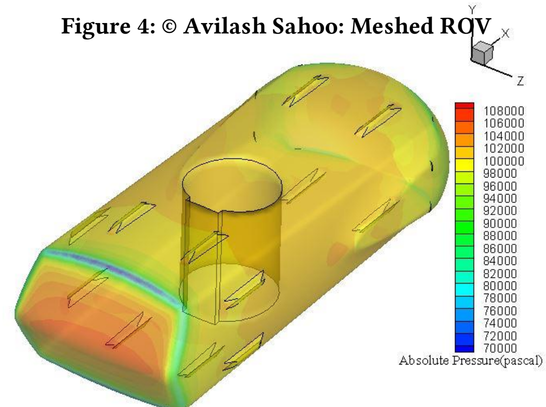

Figure 5: © Avilash Sahoo: Pressure contour

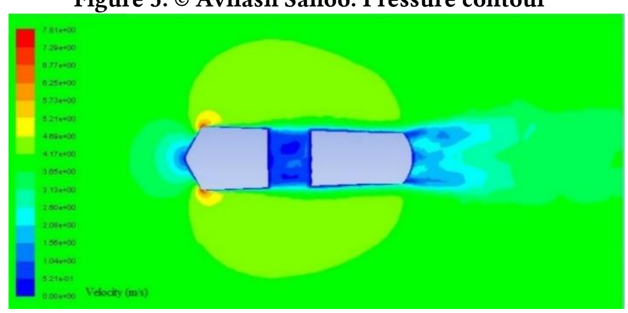

Figure 6: © Avilash Sahoo: Velocity contour

2.2.2.4 Maximum thrust required. ANSYS simulation is carried out to find drag force at different flow velocities of water past the ROV. Results are given in Table 2. From Table 2, it is observed that the ROV will experience 60 N of drag force for 4 m/s flow rate in still water. If the river flow is 2 m/s, then with 60 N force the ROV can move at 2 m/s upstream. 2 m/s travel speed is high enough for such a compact ROV. For horizontal motion two thrusters are being used hence, each should produce more than 30 N of force at maximum.

Table 2: Drag at different flow velocity

Flow velocity (in m/s)	Avg. Drag (in N)
1	8.7
1.5	14.6
2	23.8
2.5	34.13
3	39.17

3.5	46.79
4	59.26
4.5	71.75

2.2.3 Thrusters. T200 thrusters from bluerobotics [6] can produce up to 3.55 kgf of thrust when operates at 12 volt which gives maximum 34.81361 N of force. As these thrusters produce more than 30 N force, they are considered for the ROV. These Underwater thrusters are specially designed for marine robotics. The T200 is made of high-strength, UV resistant polycarbonate injection molded plastic. It has an integrated Electronic Speed Controller (ESC) which is exposed to water eliminating heating issues.

2.2.4 Maximum velocity. Using the data in Table 2, a quadratic curve is fitted using MATLAB (see Fig. 7) which gives a relationship between drag and velocity as:

$$\text{Drag} = 1.399\,u^2 + 9.895\,u - 2.349 \tag{1}$$

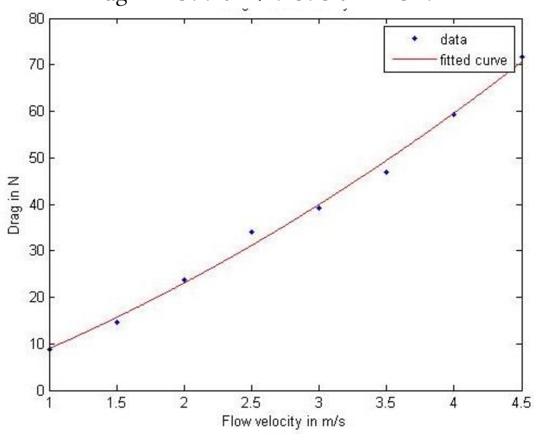

Figure 7: © Avilash Sahoo: Velocity vs drag graph.

Here 'u' is the velocity in the horizontal plane. Maximum drag the robot can withstand is 69.6 N, which is sum of the maximum force supplied by two thrusters. Substituting drag as 69.6 N the velocity comes out to be 4.46 m/s. Hence, the maximum velocity achievable is 4.46 m/s in still water, which is the maximum possible relative velocity between water and the ROV. Therefore, if the ROV is moving upstream, then the velocity of water (in m/s) subtracted from 4.46 m/s is the maximum achievable velocity of the ROV.

2.2.5 Stress analysis. The ROV will experience hydrostatic pressure due to water head and hydrodynamic pressure due to its movement. If the hull is not strong enough it may develop crack under pressure. Stress analysis is carried out to ensure the hull will not fail under water pressure.

Hydrostatic pressure can be calculated using the formula:

$$\text{Pressure} = \rho g h$$

where ρ is the density of the fluid (i.e water) = 1000 kg/m^3.

g is the acceleration of gravity = 9.8 m/s^2.

h is the height of the water head above the ROV.

Hydrodynamic pressure is evaluated from the flow simulation in section 2.2.2.3. Using these pressures as load stress analysis has been carried out in ANSYS. FRP is considered as body material of the model. The central hole on the body is set as a fixed surface. The model is solved to get the stress and strain developed (see Fig. 8). This process is repeated with different depth. The average depth of the river is around 30 to 40 meter. Here stress developed at 100-meter depth is around 771 kpa, less than limiting stress of the material (1400 Mpa), therefore the body can withstand water pressure even at 100m depth without failure.

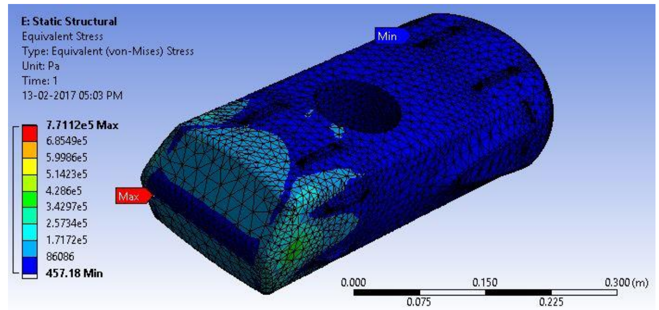

Figure 8: © Avilash Sahoo: Stress contour

3 ROV DESIGN

Numerical analysis carried out in sections 2.2.2 and section 2.2.5 ensures the base model fulfills the design requirements. In this section, the base model is upgraded to a practical working design with the required components.

3.1 Mechanical Design

Hull structure is developed around the central thruster. Hull is made of three-part modular structure to have associability to all internal components. Front-section houses the camera module with led light and having a transparent acrylic sheet in front of cameras. The acrylic panel is mounted on the front part using screw joints with a rubber gasket in between. Mid-section of the hull houses the central thruster in the middle hole. In front of the central thrusters is the battery and on the back are the microcontroller, power distribution module, and other setups. Other two thrusters are mounted on the sides of the mid-section. Rear section houses the sensor housing, LAN connection setup, on-off switch and charging port. Figs. 9 and 10 shows the ROV design and dimensions, and Fig. 11 shows the ROV with its internal components.

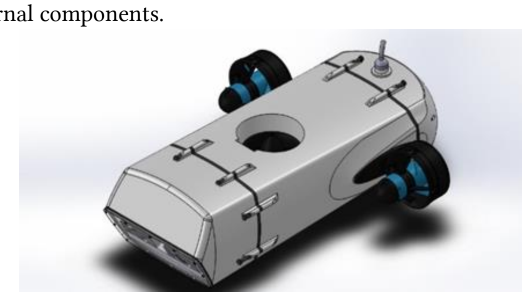

Figure 9: © Avilash Sahoo: CAD model of the ROV

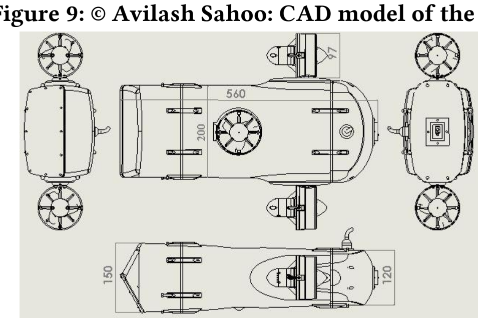

Figure 10: © Avilash Sahoo: Dimensions of the ROV.

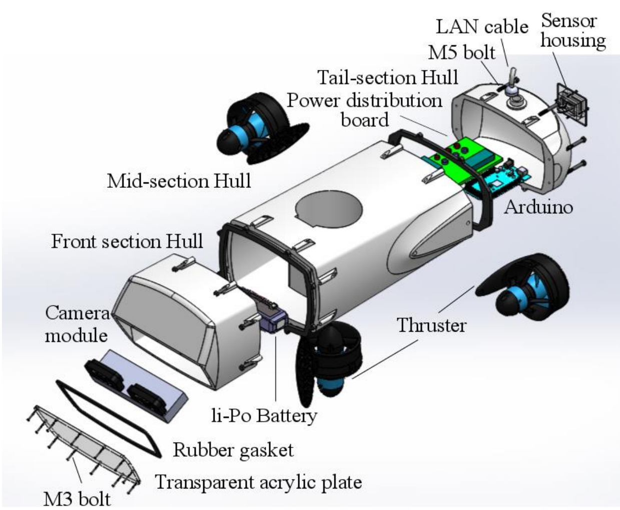

Figure 11: © Avilash Sahoo: Components of the ROV.

3.1.1 Manufacturing. GFRP is selected as body material because of its several benefits as discussed in the section 2.2.1. The ROV body is manufactured in the mechanical workshop of IIT Guwahati with little use of complex tools. First, a solid replica of the CAD model is made from thermocol blocks using hotwire cutting setup and sand paper. Using the termocol model Plaster of Paris (POP) molds are prepared. Then alternate layers of fiberglass sheets and resin are applied on the POP molds and allowed to dry. Molded parts are joined to get the three parts of the hull. Assemble surface are leveled, thrusters are mounted and connection passages are drilled. All passages are sealed properly and each part is checked for water leakages. The parts are assembled to get the ROV shown in Fig. 12.

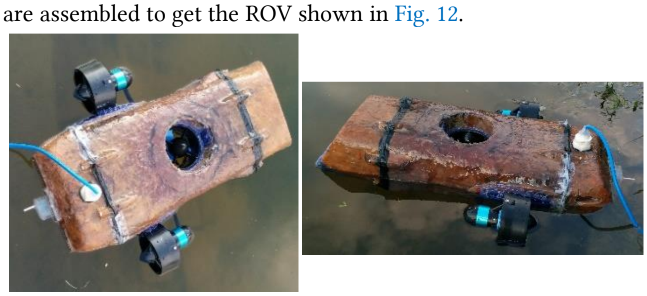
Figure 12. © Avilash Sahoo: Developed ROV.

3.2 Electronics Design

3.2.1 Sensor integration. Sensors are an essential part of a ROV as it provides quantitative information of its surrounding. This ROV has temperature and pressure sensor ***(see Figs.** 13 & 14)* which measures real-time temperature and pressure data. This pressure data is being used to calculate the depth of the ROV from the water surface. These sensors must be exposed to the surrounding water and at the same time should maintain a watertight connection to the microcontroller inside the ROV. So, a sensor housing is developed by gluing laser cut acrylic sheets and fitted to the rear section of the ROV. After placing the sensors, the housing is sealed with silicone sealant to prevent any water leakage. The sensor housing can have different sensors to measure various parameters such as dissolved oxygen quantity, RH, turbidity, flow velocity. This quantitative information will help understand the river ecology better. ROV is also equipped with a dual camera setup (see Fig. 15) with led light. These cameras can record and live stream underwater footage in high definition. Sonars are used for obstacle avoidance and object detection but they are expensive. Object detection algorithms can be used with the live video to avoid collision with the obstacles on its path for a compact low cost ROV.


Figure 13: Pressure


Figure 14: Temperature sensor.


Figure 15: Dual camera setup with led.

3.2.2 Control and communication. All the electronics and cameras are securely sealed inside the ROV. All communication is through the LAN cable to the ground control station. Ground control station contains a laptop and a controller. USB to LAN extender adapters are used at each end of the LAN cable to enable communication between the laptop and the electronics component inside the ROV. Live underwater footage and real-time sensor data are being displayed on the laptop which also records this information. The controller is connected to the laptop for control the movement of the ROV. ARDUINO and two cameras are connected to the USB hub. USB hub draws power from the board and connected to the LAN cable by female USB to LAN adapter. Other end of the LAN cable is connected to the laptop using a LAN to male USB adapter. Detailed communication layout is shown in Fig. 16.

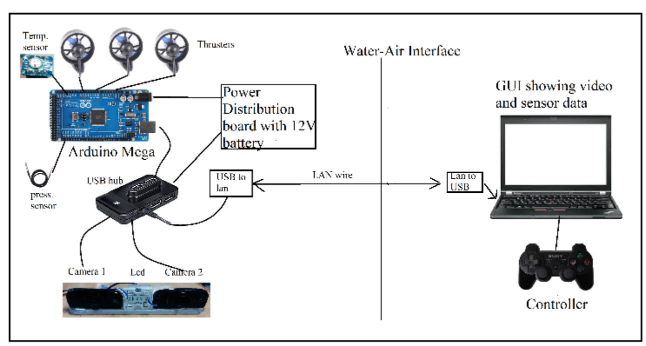

Figure 16: © Avilash Sahoo: Electronics connection

3.2.3 Power distribution. ROV is operated with a 12v 3 cell Lithium polymer battery placed inside the body. A power distribution board is developed as shown in Fig. 14. This board distributes power from the battery to three thrusters. The led attached to the camera receives power from this board through a 5v relay, which is controlled by Arduino hence, the user can remotely switch the led on and off when required. One terminal of the battery is bypassed through a switch which is placed on the rear section of the ROV. The cameras are attached to a USB hub which takes a 5-volt connection from the board. To supply 5 volts to the hub a dc to dc step-down buck converter is attached to the power board. Power distribution layout is presented in Fig. 17.

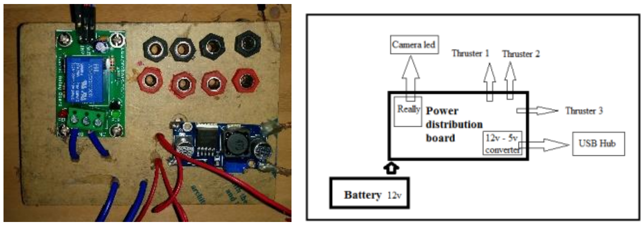

Figure 17: © Avilash Sahoo: Arrangement of components.

4 FIELD TEST AND CONCLUSION

4.1 Field Test

ROV should be watertight to ensure its smooth working as it contains electronics inside and weight of the ROV increases with water leakage. After sealing the passages and connections each section of the three-part ROV is inspected for water leakage. After successful water leakage test, the sections are connected using screw joint with rubber gaskets in-between. These rubber gaskets under pressure prevent water leakage into the ROV. The assembled model is placed underwater for an hour and found to has no water leakage.

When the ROV is deployed in the lake for the first time it is found to be floating on the surface as shown in Fig. 18. Weights are added around the central thruster in form of cast iron plates until it submerged fully to achieve neutral buoyancy.

During the first trial run of the ROV in the swimming pool, it is found to perform required horizontal and vertical motions without any difficulties. The real-time sensor data and video footage are being displayed on the laptop on the surface.

Figure 18: © Avilash Sahoo: Field Test of the ROV.

4.2 Conclusion

This paper presented a compact low-cost ROV design for river exploration. The ROV can be used for underwater survey to better understand the underwater ecology, physical phenomenon and underwater life by providing underwater footage and other quantitative information using the camera and other sensors. To make the model compact it has a minimalistic three thruster design. As the model is neutrally buoyant the vertical motion can be carried out using only one thruster which helps in achieving better energy efficiency and compactness. The ROV has a modular three-part design for ease of assembly and accessibility of internal components. Required hydrodynamic analysis has been carried out to figure out the drag forces for selecting the appropriate thruster and also the maximum travel velocity which is 4.46 m/s in still water. Stress analysis has also been carried out to ensure its operational safety up to a depth of 100 m. The ROV body is made of glass fiber composite and fitted with thrusters, microcontrollers and required sensors for its operation. ROV is connected to ground control with a LAN cable, which transmits the control signal along with real-time underwater footage and sensor data. This ROV can Transmit and record live underwater footage, real-time temperature and pressure data for different ecological study. Pressure data is being used to estimate the depth of the ROV from water surface. The ROV is successfully field tested. Such low-cost compact ROVs can go a long way in helping the local educators and environmentalist in their exploration and research.

5 FUTURE WORK

- Different sensors to measure parameters such as dissolved oxygen quantity, RH, turbidity, flow velocity etc. can be integrated into the sensor housing depending on the exploration objective.
- Stereo vision and object detection algorithms can be used with the live video footage for collision avoidance, position estimation, and object detection.

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