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Design and Development of Underwater Robot

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***Abstract* - Majority of the design proposed for under water robots have been either biomimetic or motor driven thruster operated. This paper presents a novel design for a 4 degree of freedom thruster operated under water robot minimizing the effect of drag during under water navigation. In the paper possible hull shapes were analyzed. After deciding the shape, pressure distribution and drag forces were calculated. Depending on the result, the mathematical model was built based on suitable assertion. The calculations justify the efficiency of using a cylindrical hull and two perpendicular pairs of thrusters for the underwater robot. Finally, the paper also presents electronics and communication system suitable for the robot considering possible difficulties which may be encountered during underwater navigation.**

Key words - Under water robotics, biomimetic, thrusters, drag force, communication systems

I. INTRODUCTION

Development of underwater vehicles have provided researchers the tool to explore deep seas as well as to examine the adverse effects of human activities on underwater ecosystems by helping them to acquire enormous amounts of data crucial for understanding deep sea life.

Underwater robots are classified into two categories- Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). ROVs are tethered to a land location or a ship. The tether serves to supply power and facilitate communication. ROVs are highly maneuverable. AUVs on the other hand are free of tethers and have on-board power supply. ROVs are extensively used in offshore oil and gas installations, performing tasks such as debris removal, cleaning and operating variety of testing tools. AUVs are mainly used for underwater scientific surveys, such as underwater archaeology and under-ice surveys. Military applications of AUVs include mine detection and landing site survey.

Underwater robots come in all kinds of shapes such as torpedo-shaped, rectangular, spherical etc. Recently, even bio-inspired robots have been developed which mimic navigation techniques of aquatic animals such as fish, turtles, octopus etc. Power sources used for underwater robots include batteries, accumulators, fuel cells etc. Robots operating in shallow water can also use solar energy as power source.

The first AUV of torpedo shaped was SPOV manufactured by University of Washington Applied Physics Laboratory maximum speed of 2m/s and maximum achievable depth of just 3.6 m

In this paper, first shapes for the robot were analyzed. Dimensions are decided according to the components required in the robot. Simulation results are then given for the calculated dimensions. Using these results, mathematical model for the underwater robot system is developed which is then simplified based on certain assertions**.** At the end the suitable communication technique for the robot is presented.

II. DESIGN OF THE ROBOT

The robot design consists of a central hull, which acts as a leak proof chamber for housing the electronic components, and 4 tl Hull utside the hull. The thrusters will be connected to central hull through arms and thrusters on two opposite arms will have vertical axis for heave motion while the other two will have horizontal axis for surge motion. The electronic component consists of 2 Lipo batteries of dimension 14cm x 3.5cm x 4.2cm & 430gm weight with 11.1 volt, 5Amph capacity; 4 electronic speed controller (ESC) of dimension 5.5cm x 8.7cm x 0.7 cm & 28 gm weight for controlling thrusters speed; & arduino Mega 2560 microcontroller of dimensions 11.4cm x 1.3cm x 5.7cm, 46gm weight for controlling ESC and acquiring data from sensor. Each thruster weighs 295 gm in air and 120 gm in water. These components are selected based on kinematic constraint. The material for the hull and the arms was decided to be acrylic because of its low weight, transparent property & moderate strength.

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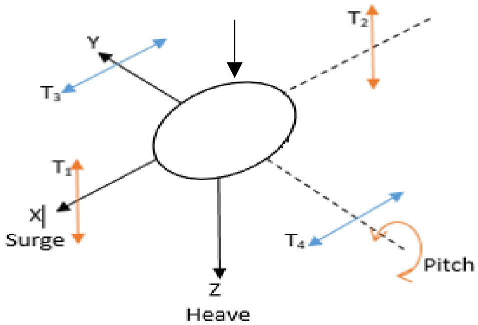

Fig. 1 Robot Schematic

Initially, for the shape of the hull, spherical and cylindrical shapes are analyzed.

A. *Spherical Hull*

The largest components in the hull are the two batteries. Thus, the batteries limit the minimum radius of the sphere. To achieve least possible size of sphere, both batteries will have to be kept near the center in each hemisphere. i.e., they will be kept symmetrically.

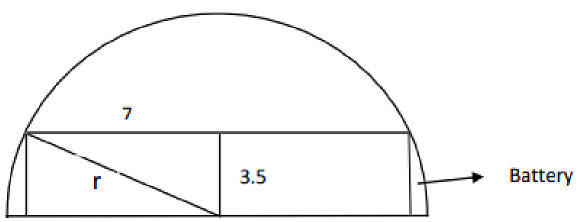

Fig. 2 Position of batteries inside the upper hemi spherical hull

As shown in Fig. 2, inner radius of the sphere, *r* can be determined by

$$r = (7^2 + 3.5^2)^{1/2} = 7.83 \text{ cm} \quad (1)$$

Rounding this to 8.5 cm (space for wires at the battery terminals) and considering thickness of acrylic to be 0.5 cm, the outer radius of sphere is found to be 9 cm. Volume of the hull = $\frac{4}{3}\pi(9)^3$ = 3053.6 cm^3

Volume of acrylic used (Va) = $\frac{4}{3}\pi[(9)^3 - (8.5)^3]$ = 481.2 cm^3

Taking density of the acrylic as 1.2×10^{-3} kg/cm^3, mass of the hull is found to be $M_a \approx 0.578$ kg

Total mass of the robot including hull, 2 batteries, 4 ESC, Arduino, 4 thrusters is found to be:

M = 2.076 kg

For stability of a submerged object, the center of mass should lie below center of buoyancy. Hence, all other components were housed in the lower hemisphere.

Considering the volume of the hull and assuming density of water to be 1×10^{-3} kg/cm^3, the buoyant force on the robot is 30.536 N.

The net upward force = Buoyant force- Weight of the robot = 9.78 N.

For immersion, net upward force should be zero. To achieve this the dead weight has to be placed in lower hemisphere. However, after housing the rest of the components in the lower hemisphere, sufficient space is not available inside the hull to accommodate dead weight and if radius is increased for the purpose, then buoyant force will increase rapidly because of restriction to put the dead weight in lower hemisphere only. Hence the idea of spherical hull was discarded and a cylindrical hull was considered.

B. *Cylindrical Hull*

This design consists of a cylindrical hull with hemispherical ends. The minimum size of the cylinder was obtained by placing the batteries vertically and parallel to the axis of the cylinder. The microcontroller and electronic speed controllers (ESC) are kept on either sides of the batteries. The radius of the cylinder is decided by the width of the battery and the width of other components. All the ESCs are placed on one side of the battery. Minimum radius of the cylinder is,

$$R = 2.1 + 4 \times 0.7 = 4.9cm$$

Providing space for the wires, inner radius is taken as 5.5 cm. considering the length of the batteries, its terminals wire and dimension of the dead weight, the inner and outer height of the cylindrical hull is 17.5 cm and 18.5 cm, respectively. Therefore, volume of the hull is

$$V = \pi \times 6^2 \times 18.5 = 2092.3cm^3$$

And volume of hull material is

$$V_a = \pi[6^2 \times 18.5 - 5.5^2 \times 17.5] = 429.2\ cm^3$$

Mass of acrylic $M_a = 0.515\ kg$

Total mass of hull,
$M = 515 + 2 \times 430 + 4 \times 120 + 4 \times 28 + 46 = 2.013\ kg$

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Weight of hull is 20.13 N, Buoyant force is 20.92 N. Net upward force on the hull is estimated to be 0.8 N. Since this force is very small, it is decided to keep some dead weight to bring down the center of mass. Keeping in mind the total weight of the hull, the dead weight of 0.3 kg was decided (so as to not make the hull too heavy). Assuming stainless steel with a density of 8 g/cm^3, volume of the dead weight is $V_d = {}^{300}/_{8} = 37.5cm^3$ when the dead weight of 5.5 cm radius and 4 mm thick was used center of mass was found to be 3 cm below the center of buoyancy. Based on the above hull having cylindrical shape was frozen for the present case.

C. Thruster

Owing to the design aimed to be light weight, efficient and easy to control, the thruster should have efficient brushless electric motor, compact design, it should provide rotation and torque in both clockwise and counter-clockwise directions. After doing market survey it was found that the thruster T100 [1] has these properties.

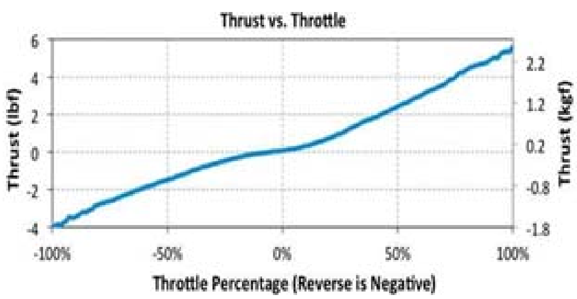

Fig. 4 Thrust vs Thottle percentage[1]

Apart from that, from Fig. 4 it is evident that the thrust vs throttle is almost linear which facilitates the control of the robot. The design also targeted to withstand in water for around 20-25 min. From Fig.5, assuming an average throttle percentage of 70% during the navigation, power consumption of each thruster is 80 Watts. Total power consumption by the thrusters is 320 J/sec.

Therefore, the total run time that can be achieved with the given thruster and battery specification is around 20 min.

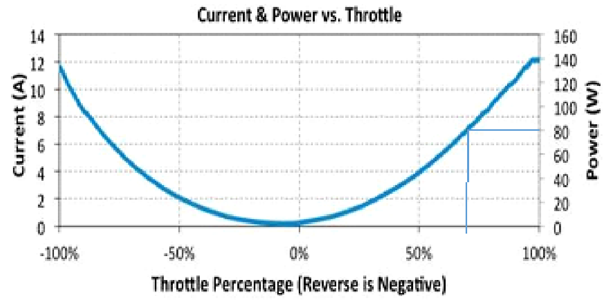

Fig. 5 Current vs Thottle percentage[1]

D. Final Design

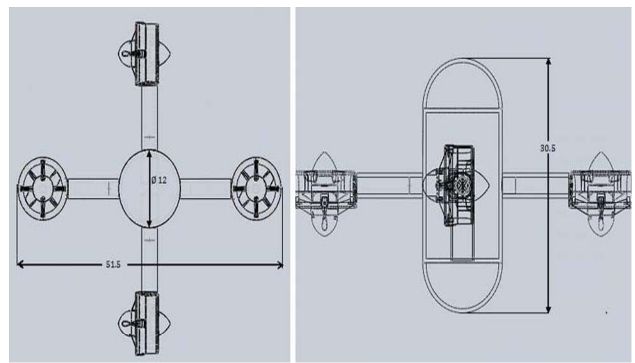

Fig. 6 Dimensions of the Robot

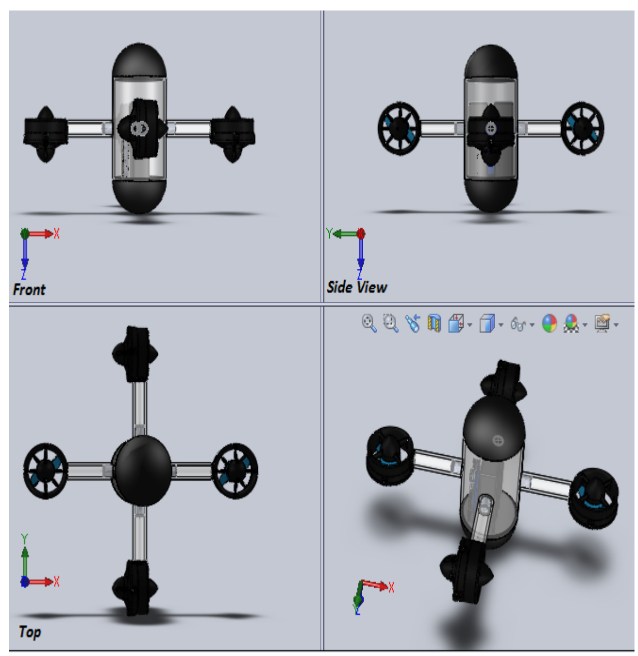

Fig. 7 SolidWorks model representing front, top, side and isometric view of the robot

Based on the above calculation, the CAD model was built in solid works with cylindrical hull of diameter 12 cm & height 30.5 cm. The final design of robot is found have weight of 3.018 kg, moment of inertia

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about Z axis (Fig.) of 0.031×10^{6} kg*cm^2 and is able to be fixed in box of 50.5×50.5×30.5 cm

III. DRAG FORCE SIMULATION

For simulating the drag force on robot, Solid works Flow Simulation software was used. For the simulation, the robot is considered to be at rest and drag force is calculated for specific fluid velocity. The drag during translation motion of the robot was investigated considering the surge and heave motion

From the pressure distribution shown in Fig.8, it evident that the pressure in front of the robot is high compared to rear side resulting in the drag. The simulation was carried out for different velocities

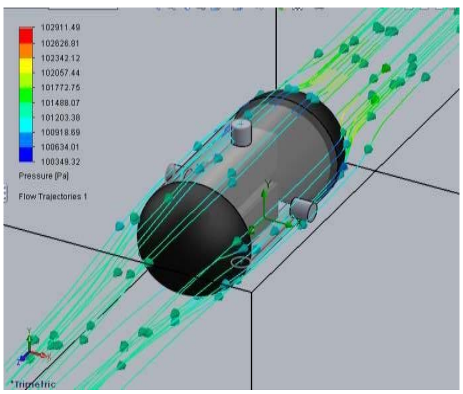

Fig. 8 Pressure distribution for the velocity of 2 m/s.

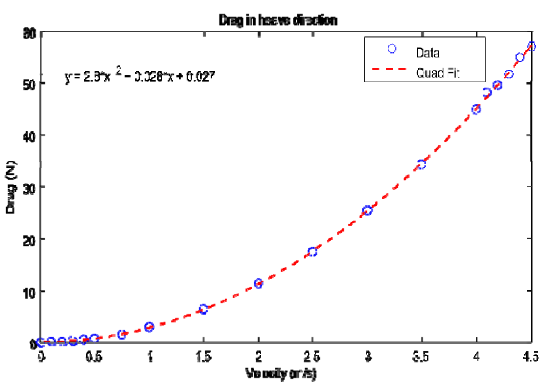

Fig. 9 Drag (F) vs. velocity (V)

Fig.9 shows variation the drag force vs velocity plot for heave motion. The curve indicates a polynomial fit of order 2 in the form $F = 2.8V^2+0.028V+0.027$, Neglecting the last two terms, F is proportional to V^2.

The maximum thrust that can be achieved by the two thrusters is 46 N and the corresponding terminal

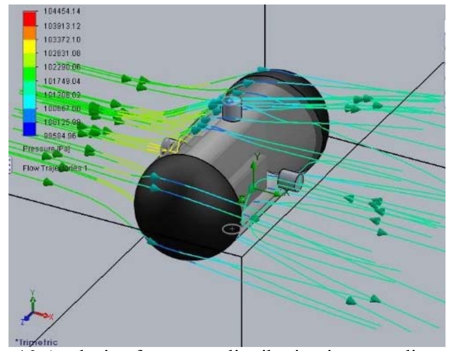

Fig. 10 Analysis of pressure distribution in surge direction for 2m/s.

velocity of the robot in the heave direction is estimated to be ≈ 4 m/s.

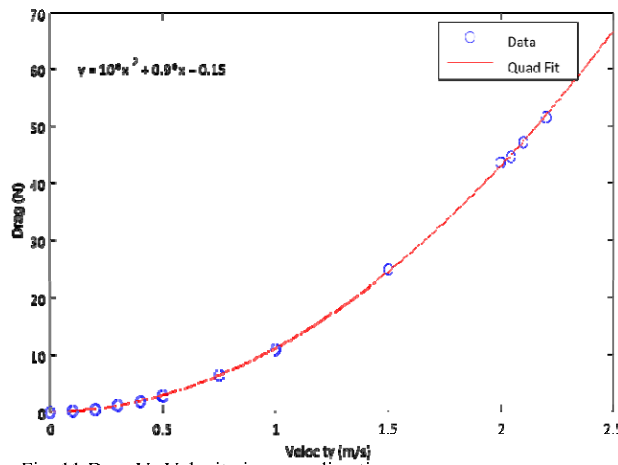

Fig. 11 Drag Vs Velocity in surge direction

Similar analysis resulted in the expression for drag force along surge direction as (Fig.11),

$F = 10V^2 + 0.9V - 0.15$, Here also it is observed that F is proportional to V^2. The estimated terminal velocity of robot in surge direction ≈ 2.2 m/s.

IV. MODELING OF ROBOT

The dynamic model of the robot is presented in this section is based on the underwater robotic models proposed by Fossen [3] and Yuh [4]. The dynamic model is derived from the Newton-Euler motion equation and is given by,

$$M\dot{V} + C(V)V + D(V)V + G = T \qquad (2)$$

where, *M* is the mass and inertia matrix, *C(V)* is the Coriolis and centripetal terms matrix, *D(V)* is the

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hydrodynamic damping matrix , G is the gravitational and buoyancy vector, T is the external force and torque input vector, and V is the velocity state vector.

Assertions are made on the dynamics of the robot for simplification based on the justification provided by Ridao et al. [5]. The approach assumes decoupling between the degrees of freedom. By decoupling the Coriolis and centripetal terms matrices become negligible and hence can be eliminated from the dynamic model.

The simplified dynamic model for the AUV becomes,

$$M\dot{V} + D(V)V + G = T \tag{3}$$

A. Mass and Inertia Matrix

M consists of both a rigid body mass and inertia, M_{RB}, and a hydrodynamic added mass, M_A. That is,

$$\mathrm{M} = \mathrm{M}_{RB} + M_A \tag{4}$$

Considering the body frame to be positioned at vehicle's center of gravity the mass m =3.18 kg, I_Z = 0.031×10^6 $kg * cm^2$, then M_{RB} is expressed as:

$$M_{RB} = \begin{bmatrix} 3.18 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.18 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.031\times10^6 \end{bmatrix}$$

i.e. M_{RB} = diag {3.18 0 3.18 0 0 0.031×10^6}

For simplicity added mass can be modeled as some volume of fluid moving with the object. With the robot's body is almost symmetrical, added mass matrix is simplified to

$$M_{RB} = \begin{bmatrix} 2.54 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.45 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

where, M_{RB} (1, 1) is the x direction added mass $= \frac{2}{3}\rho_w \pi R^3 + \rho_w \pi R^2 L = 2.54\ kg$ and M_{RB} (3, 3) is z direction added mass $= \frac{2}{3}\rho_w \pi R^3 = 0.45\ kg$

B. Hydrodynamic Damping Matrix

The hydrodynamic damping matrix represents the drag and lift forces acting on a moving underwater vehicle. However, for a low-speed underwater vehicle, the lift forces can be considered negligible when compared to the drag forces. These drag forces can be separated into two different terms consisting of a linear and quadratic term. That is,

$$D(V) = diag\{D_L + D_Q|V|\} \tag{5}$$

where D_L and D_Q are the linear and quadratic damping terms respectively.

$$D_L = diag\{X_u \quad Y_v \quad Z_w \quad K_p \quad M_q \quad N_r\}$$

and,

$$D_Q = diag\{X_{u|u|} \quad Y_{v|v|} \quad Z_{w|w|} \quad K_{p|p|} \quad M_{q|q|} \quad N_{r|r|}\}$$

The damping matrix,$D(V)$, using simulation result is given by

$$D(V) = \begin{bmatrix} 0.9+10u & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.028+2.8w & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_r + N_{r|r|}|r| \end{bmatrix}$$

E. Gravitational and Buoyancy Vector

The gravitational and buoyancy vector, G, is defined as,$G = \begin{bmatrix} f_B + f_G \\ r_B \times f_B + r_G \times f_G \end{bmatrix}$

(6)

Where f_B is the buoyant force vector, defined as,

$$f_B = \begin{bmatrix} 0 \\ 0 \\ -20.3 \end{bmatrix}$$

f_G is gravitational force vector defined as

$$f_B = \begin{bmatrix} 0 \\ 0 \\ 30.35 \end{bmatrix}$$

r_B is the center of buoyancy and r_G is the center of gravity. As body frame is positioned at the center of gravity, then $r_g = [0 \quad 0 \quad 0]^T$. Since the roll and pitch are negligible, equation Eq. (6) simplifies to,

$$G = [0 \quad 0 \quad 10.05 \quad 0 \quad 0 \quad 0]^T$$

F. Force and Torque Vectors

The external force and torque vector can be expressed as, $T = LU$

where, L is the mapping matrix and U the thrust vector expressed as

$$U = [T_1 \quad T_2 \quad T_3 \quad T_4]$$

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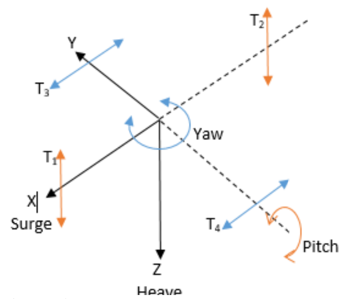

Fig.12 Robot Schematic

T_i represents thrust from the 4 thrusters shown in Fig.12. The mapping matrix *L (in m)* is a 6 × 4 matrix that uses *U* to find the overall forces and moments acting on the vehicle. Since all the thrusters are equidistant from the center of the robot, mapping matrix according to the CAD model dimensions becomes:

$$L = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -0.208 & 0.208 \\ 0.208 & -0.208 & 0 & 0 \end{bmatrix}$$

$$U = [T_1 + T_2 \;\; 0 \;\; T_3 + T_4 \;\; 0 \;\; 0.208(-T_3 + T_4) \;\; 0.208(T_1 - T_2)]^T$$

In *U* matrix, the first three rows signify the effect of a particular motor on the movement of the AUV along the x, y and z directions and the last three rows signify the moment provided by the thrusters.

V. COMMUNICATION SYSTEM

The sound, electromagnetic (EM), or optical waves communication suffer from slower speed, low range, large antenna size and also include communication paths that cross the air-water boundary which further introduces problems of reflection, refraction[6]. Hence Bouyant communication system is suitable for the robot [7].

From Fig.12 it can be seen that, the three main circuits of given communication system are: an underwater transceiver, an interface circuit and an in-air transceiver. Cable connects the underwater transceiver to the interface circuitry encapsulated in the floating buoy, which transfers the electrical signals between the underwater transceiver in the submerged body to the interface circuitry in the floating buoy. The buoy not only keeps the interface circuitry water-proof, but it also acts as a floating agent for holding and erecting the in-air antenna.

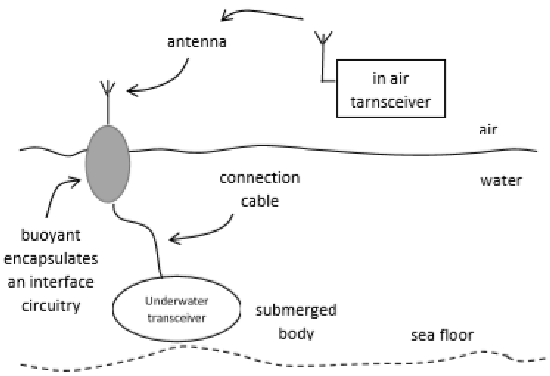

Fig. 13 Schematic of buoyant communication system

On the in-air side, the electrical signal received from the interface circuit is converted into electromagnetic waves with the help of in-air antenna. This transmitted electromagnetic wave is then received by another in-air antenna attached to another part of an in-air transceiver. On the way back, the complete procedure is reversed to send an electrical signal generated by the in-air transceiver to the underwater transceiver. In both two way communication, the propagation of electromagnetic waves is simply dependent on a pair of in-air antenna without the need to cross the physical boundary of air-to-water.

VI. ELECTRONICS

A. Arduino Mega

For handeling electronics component such as thrusters, sensors etc., microcontroller is needed. As Arduino microcontroller has user-friendly GUI & lot of resoursec are avilable, it will be used in the robot.

B. ESC

An electronic speed control (ESC) is an electronic circuit with the purpose to vary the brushless DC motors speed, its direction and possibly also to act as a dynamic brake. It is an intermediate between microcontroller and BLDC motor. An ESC interprets the signal from microcontroller and actuate the magnetic field around the according to signal which in turn rotate the motor at some specific speed. The back EMF from the motor is used by the ECS as feedback signal.

C. Inertia Measuring Unit(IMU)

IMU is used to measure the heading of robot. It consist of 3-axiz accelerometer, 3 axis gyroscope and 3 axis magnetometer. The roll, pitch & yaw will be

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calculated by based on the signals from the sensors, which will be used to controll of robot.

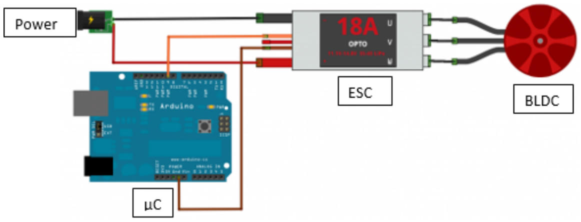

Fig. 14 Connetion of ESC to µc

VII. SUMMARY

In this paper we discussed about all the work done till now on this project. It was decided that the robot will have a central hull with propellers as thrusters. The possible shapes of hull were narrowed down to sphere and cylinder. After sufficient analysis, cylindrical hull was found to be a better choice than spherical hull. Dimensions were calculated and flow simulation was performed. This gave us drag as a function of velocity, using which we calculated terminal velocities of the robot. Mathematical modelling was done which will be used for formulating the controller. We also analyzed various underwater communication techniques. Buoyant communication system was found to be most appropriate for our purpose.

VIII. ACKNOWLEDGEMENT

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