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Design and Analysis of a Novel Underwater Glider - *RoBuoy*

Thiyagarajan Ranganathan[1], Sundaravalli Aravazhi[2], Sambit Mishra[3] and Asokan Thondiyath[4]

***Abstract*— Underwater gliders are special class of autonomous underwater vehicles (AUVs) proven to be power efficient with better range and endurance compared to the conventional underwater robots. Most of the existing underwater gliders use 'change of mass' based variable buoyancy (VB) method in which the overall system architecture and construction are complex. A novel underwater glider *RoBuoy* based on the 'change of volume' concept of variable buoyancy method is presented here. *RoBuoy* uses actuated metallic bellows to change the volume which makes the system simple and modular in construction without any compromise in the performance. It uses minimal number of parts compared to the existing gliders which reduces the overall complexity of the system. Also, most of the conventional gliders use the external fluid for its working which may result in corrosion or fouling of parts and requires frequent maintenance. In the proposed glider, all the vital parts required for its working, apart from the sensing payloads are enclosed inside the hull, thereby increasing the durability. In this paper, a detailed design of *RoBuoy* is discussed with its possible modes of operation. An integrated mathematical model considering the individual dynamics of the actuator, hull/fuselage, and the wings has been developed and the open loop performance of the glider is studied at different input conditions. An experimental prototype has been designed and fabricated based on optimized dimensions, with the required mechatronic system. Experiments have been conducted and the results prove the feasibility of the concept.**

I. INTRODUCTION

Underwater robots are vital '*field and service*' class robots which help visualize and apprehend the underwater world [1]. These robots are equipped with advanced sensors and actuators, which can be used for sampling the ocean, understanding the underwater biodiversity, manipulation, installation of underwater structures, salvaging and various other applications where the human reach is impossible. The design of underwater robots is critical and usually complex because of the environmental constraints. The depth of operation especially is one of the critical factors which demands special consideration while designing. It is worthwhile to mention that a robot designed for operation at higher depths will be inefficient to be operated at shallow depths and the converse is not possible at all.

[1]Thiyagarajan Ranganathan is with the Robotics Laboratory, Department of Engineering Design, Indian Institute of Technology Madras, Chennai-600036, Tamil Nadu. India. (E-mail: thiyaguiitm@gmail.com)

[2]Sundaravalli Aravazhi is with the Department of Instrumentation and Control Engineering, National Institute of Technology, Tiruchirappalli-620015, Tamil Nadu. India. (E-mail: sundaravalli.aravazhi@gmail.com)

[3]Sambit Mishra is with the Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai-600036, Tamil Nadu. India. (E-mail: sambit98@gmail.com)

[4]Asokan Thondiyath is with the Department of Engineering Design, Indian Institute of Technology Madras, Chennai-600036, Tamil Nadu. India. (E-mail: asok@iitm.ac.in)

Underwater gliders are a division of underwater robots which uses variable buoyancy mechanism to dive across the water column [2]. They are mostly designed and used for shallow water applications. Variable buoyancy is a classical, power efficient method to provide heave motion which has been used in many of the existing underwater systems [3]. The heave motion can be conveniently vectored along surge direction using control planes like wings, thus resulting in the design of underwater gliders. These gliders have 3 degrees of freedom (DoF) namely surge, heave and pitch. The overall system is under-actuated and these DoFs are coupled in the sense that the surge and pitch motions are effected through heave motion alone. Advancement to the conventional gliders is the hybrid gliders which use thrusters along with the variable buoyancy mechanism. Such gliders offer additional range and speed at the cost of reduction in the endurance. Apart from the complexity in the overall design of underwater robots compared to the ground/aerial robots, some of the other design related issues to be addressed are sealing, subsystem complexity, and interaction/usage of surrounding fluid. Few of the major problems which are presently being researched upon are the design, range, endurance and autonomy [2], [4], [5], [6].

Some of the state-of-the-art gliders currently being used and researched upon are discussed here. A detailed analysis of the dynamics and control of underwater gliders is presented in [2], [7], [4]. The capabilities and applications of the gliders along with the possible sensory payloads are reported in [8]. Miniature gliders are of recent interest to develop a swarm environment underwater and to cooperatively navigate for better task handling [9]. Slocum and Seagliders are well known gliders being used for different purposes [5]. Hybrid gliders are also being used which are additionally powered using thrusters, to increase the speed of operation [6]. Modelling and performance analysis of these gliders are explained in [8]. Identification of the dynamic parameters of the glider is a challenging part for these kind of gliders with coupled degrees of freedom. Some of the system identification techniques for underwater glider are explained in [10].

In most of the existing underwater gliders, the variable buoyancy subsystem use a ballast which consists of a pump to fill/empty the ballast tank, multiple valves to direct the flow, individual drives for each valves, and tubing [8]. Since external fluid is used to vary the self mass, filters are required to avoid clogging of moving parts in pump or syringe. Use of external fluid may result in fouling or erosion of parts, especially the pumps and valves, requiring periodic servicing. Also, all the parts are to be carefully positioned

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inside the hull in such a way that the center of gravity (CoG) and the center of buoyancy (CoB) are aligned without creating any pitching moment. In most cases, the ballast will be partially filled, because of which, there will be a motion of the fluid inside the ballast whenever the glider moves. This will affect the overall dynamics and there will be a slight, continuous variation of CoG of the system. To avoid such disturbances, few gliders are designed with large syringes activated by motor-leadscrew mechanism to take-in or push-out the surrounding water [11]. Some gliders use mass shifting mechanisms to pitch, in addition to variable buoyancy systems [4].

As mentioned earlier, the underwater glider *RoBuoy* presented here uses variable buoyancy mechanism based on 'change of volume' concept. Single degree of freedom variable buoyancy modules using similar concept to achieve heave motion is discussed in [12]. An actuated metallic bellow is used to change the volume of the overall system and thereby varying the buoyancy. The bellows are expanded/compressed using linear actuators (LA). The motion dynamics is purely dependent on the expansion/compression of the bellow. Also, the proposed glider does not take external fluids inside and all the parts are concealed inside the bellow. Though the current prototype is designed for shallow water applications (up to 20 m), the concept is valid to be used even at greater depths using suitable actuators (pneumatic or hydraulic) and flexible chamber (rubber or composite material) to handle the hydrodynamic pressure. Hence the proposed system is simple in construction and uses fewer components compared to the conventional gliders.

II. *RoBuoy* - Design and Working Principle

A. Conceptual Design

The major difference in the concept between the existing underwater gliders and the one presented here is the method used for variable buoyancy. Instead of the 'change of mass' concept, the 'change of volume' concept is employed here. The overall volume of the glider changes without affecting the mass, thus resulting in a difference between the weight and buoyancy, which leads to the heave motion. The change in volume also changes the position of CoB with respect to the body co-ordinate frame. The changes in the position of CoG and CoB leads to a pitching moment and pitching motion of the glider. Two different modes of operation are possible based on the method of actuation and they are discussed in detail in Section. II-B.

The conceptual CAD design of *RoBuoy* along with the right handed co-ordinate frames (global and body frames) are shown in Fig. 1. The global co-ordinates is represented as $O_G : \{X_G, Y_G, Z_G\}$ and the body co-ordinate frame as $O_B : \{X_B, Y_B, Z_B\}$. O_B is fixed at the volumetric center, when the system is neutrally buoyant. The most important part of the glider is the hull, which is made up of bellow. Linear actuator assembly, wing assembly, and nose and tail structures are the other attachment parts to the bellow. The metallic bellow encloses the actuator and the necessary electrical and electronic parts. The prototype *RoBuoy* is

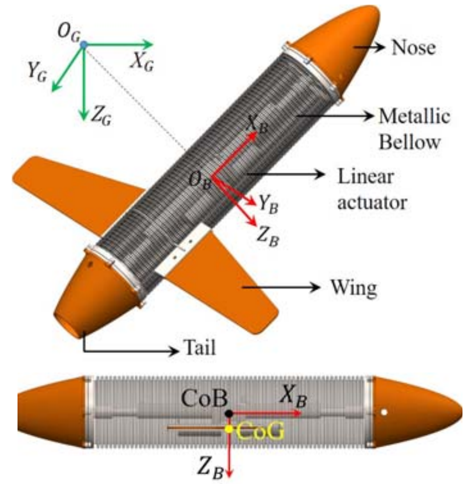


Fig. 1: Conceptual diagram

designed to be operated up to a depth of 20m. It uses two linear actuators to actuate the metallic bellow and the linear actuators are connected back to back. In Fig. 1, the hull is shown semi-transparent to show the positioning of linear actuators. The hull is locked at atmospheric pressure, filled with air. Wing assembly includes a rigid wing with its attachment mechanisms. Wings can be suitably designed and located at optimal positions to vector a component of the residual buoyant force (difference between the weight and buoyancy) along surge direction. Nose and tail are faired in a way to reduce drag effects. Figure 1 also shows the location of CoG: $\{x_g, y_g, z_g\}$ and CoB: $\{x_b, y_b, z_b\}$ with respect to the body centered co-ordinate frame, at neutrally buoyant condition of the system. By design, it is ensured that the CoG is always below the CoB which in turn ensures roll stability. A detailed internal view of *RoBuoy* is shown in Section. V.

B. Working Principle

The glider is initially designed to be neutrally buoyant, where the weight (W) is equal to the buoyancy (B). The difference between the weight and the buoyancy forces ($W - B$) is termed as residual buoyancy (b). When the bellow is compressed by retracting the pistons of linear actuators, the glider becomes negatively buoyant ($b > 0$) and starts to sink (heave). Similarly when the bellow is expanded, the glider becomes positively buoyant ($b < 0$) and starts to surface. In both the cases the weight remains the same and only the buoyancy changes due to the change in volume. Now, the pitch (θ) degree of freedom, which is rotation about Y_B is to be achieved in order to vector the residual buoyancy. Pitch can be achieved by one of the two methods discussed below.

First method is based on the restoring moment created due to misalignment of CoG and CoB parallel to Z_G. CoB in the presented prototype is approximately the volumetric center of the hull which can be anywhere along X_B based on the compression/expansion of the bellow. There will be a shift in the location of CoG also, but it is insignificant compared to the change in location of CoB. This shifting of CoG and CoB parallel to Z_G creates a moment along Y_B which results in

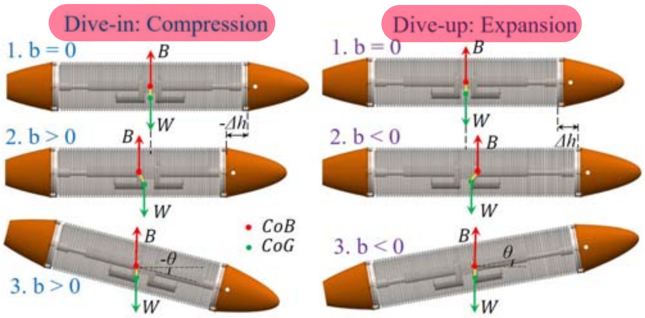


Fig. 2: Shift in CoG and CoB based on expansion and compression of bellow and the resulting dive action

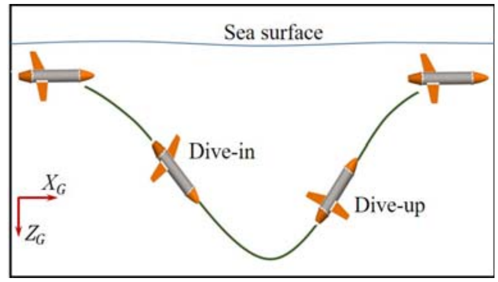


Fig. 3: Diving sequence

pitch. This pitch, along with the wing will vector the motion of the glider due to residual buoyancy (b), thus resulting in a surge motion. This is one way of gliding and in this case, only one linear actuator is sufficient to glide and the wing can be at the center of hull. A schematic diagram explaining this method is shown in Fig. 2. The second method purely relies on the position of wing. The presented prototype of *RoBuoy* is based on this concept. In this case, there will not be any shift in the location of CoB if the actuation is symmetric, as there are two linear actuators. Now, when the system exhibits heave motion, since the wings are towards the rear end of the glider, the drag on the wings will create a pitch. Thus the motion due to residual buoyancy is vectored, resulting in surge motion. Similarly, by expanding the bellow using linear actuators, the glider can be made positively buoyant, thereby diving up. Nevertheless, dissimilar motion of linear actuator will result in additional pitch due to the effect discussed earlier, which can be constructively used in a way to improve the gliding performance.

Thus the three degrees of freedom, surge, heave, and pitch are achieved using any of these methods and as mentioned earlier, these degrees of freedom are coupled. By controlling the level of expansion or compression of bellows, an effective gliding performance of the glider can be achieved. A schematic of the path that can be traced by the glider in a typical operating cycle is shown in Fig.3. It is to be noticed in both the ways of operation that the residual buoyant force exists even after the termination of actuation (after maximum expansion/compression) of the metallic bellow. Hence the glider does not consume power to continue its current dive action. Only to change the direction of dive, the bellow needs to be actuated again in the reverse direction. This saves the power consumption considerably.

III. Mathematical Model

A mathematical model of the glider has been developed in order to analyse the behaviour of the system by simulation and to optimize the performance of the system by changing the design parameters. The dynamics of the system can be subdivided into three parts as,

- Dynamics of linear actuator
- Dynamics of fuselage
- Dynamics of wing

In most of the cases, the dynamics of wing and fuselage are considered together and it simplifies the dynamic model. Here, the dynamics are modelled individually providing a modular approach to optimize the design parameters.

A. Dynamics of Linear Actuator

Linear actuator is one of the vital parts of this glider which actuates the bellow. In order to maintain symmetry in the design, two similar electric linear actuators with ball screw mechanism are chosen. The choice of LA is based on the depth of operation and the required stroke. While locking the hull at atmospheric pressure, the LAs should be expanded to half the maximum stroke, and the weight of the whole system needs to be balanced in such a way that the glider is neutrally buoyant. The linear actuator is modelled as a DC motor with gear and screw mechanism attached to a piston. The stroke of each LA is represented as h_i with i representing the index of the two linear actuator ($i = 1,2$). The velocity of the piston motion is represented as v_i, and the acceleration as $\dot{v}_i$. The velocity of the piston of linear actuator depends on the input voltage V_i and the axial load acting on the piston. The load acting on the piston is based on the area of end cap of the bellow and the depth at which the glider is diving. The overall dynamics of the actuator can be expressed as given in (1). The description and values of the parameters used in equations is provided in Table I.

$$\ddot{v}_i = \left(\frac{d_r k}{2\pi g_r JL}\right)V_i - \left(\frac{k^2 + b_m R}{JL}\right)v_i - \left(\frac{b_m}{J} + \frac{R}{L}\right)\dot{v}_i - \left(\frac{d_r g R r_b^2 \rho}{2 g_r JL}\right)z - \left(\frac{d_r g r_b^2 \rho}{2 g_r J}\right)w \quad (1)$$

For both the linear actuators, (1) can be represented in state space form as shown in (2) with state vector $\boldsymbol{x}_{LA} = [h_1, v_1, \dot{v}_1, h_2, v_2, \dot{v}_2]^T$ and input vector $\boldsymbol{u}_{LA} = [V_1, V_2, z, w]^T$.

$$\dot{\boldsymbol{x}}_{LA} = \boldsymbol{A}\boldsymbol{x}_{LA} + \boldsymbol{B}\boldsymbol{u}_{LA} \quad (2)$$

The states h_1 and h_2 are part of the inputs for the dynamics of the fuselage.

B. Dynamics of Fuselage

Fuselage for the glider is the hull along with the nose and the tail. The contribution of dynamics of fuselage is significant in the overall dynamics of the system. The dynamics of the fuselage is derived based on Newton-Euler method discussed in [13], [14]. Based on the *SNAME* convention, the body velocities along surge direction is represented as u, along heave direction as w and the angular velocity along Y_B

as q. The forces along X_B and Z_B are F_X and F_Z respectively. The pitching moment along Y_B is M_P.

The equation governing the dynamics in surge, heave and pitch are given in (3), (4) and (5) respectively.

$$(m - X_{\dot{u}})\dot{u} + mz_g\dot{q} + (-m(x_g q - w) - z_{\dot{w}}w)q$$
$$-(X_u + X_{u|u|}|u|)u - \pi r_b^2 \rho g(h_1 + h_2)sin\theta = F_X \quad (3)$$
$$(m - Z_{\dot{w}})\dot{w} - mx_g\dot{q} + (-m(z_g q - u) + x_{\dot{u}}u)q$$
$$-(Z_w + Z_{w|w|}|w|)w + \pi r_b^2 \rho g(h_1 + h_2)cos\theta = F_Z \quad (4)$$
$$mz_g\dot{u} - mx_g\dot{w} + (I_y - M_{\dot{q}})\dot{q} + (m(x_g q - w) + Z_{\dot{w}})u +$$
$$(m(z_g q + u) - X_{\dot{u}})w - (M_q + M_{q|q|}|q|)q$$
$$+(z_g W - z_b B)sin\theta + (x_g W - x_b B)cos\theta = M_P \quad (5)$$

It can be noticed that the above equations are coupled and non-linear. These equations can be represented in the state space like form as shown in (6), with the state vector $\boldsymbol{x}_f$=$[x, u, z, w, \theta, q]^T$ and the input vector to the system $\boldsymbol{u}_f$ =$[h_1, h_2, F_x, F_z, M_P]^T$. The components h_1 and h_2 are outputs from the LA dynamics while F_x, F_z and M_P are the outputs from the wing dynamics discussed in Section. III-C.

$$\boldsymbol{M}\dot{\boldsymbol{x}}_f = \boldsymbol{p}(\boldsymbol{x}_f) + \boldsymbol{Q}(\boldsymbol{x}_f)\boldsymbol{u}_f \quad (6)$$

Here, $\boldsymbol{p}(\boldsymbol{x}_f)$ is a vector of non-linear equations as a function of the state vector defining the Coriolis and damping effects. $\boldsymbol{Q}(\boldsymbol{x}_f)$ is the non-linear output matrix again as a function of the state vector and $\boldsymbol{M}$ is the mass matrix defining the mass and inertial effects. The surge and heave velocities are the inputs to the wing dynamic model.

C. Dynamics of Wing

As discussed earlier, wing vectors motion along heave towards surge direction. The wing chosen here is a thin plate which can be attached to the hull at an optimal location towards the rear end of the glider. The horizontal distance between the center of the wing and the body center along X_B is d. Lift and drag are the two forces which will act on the wing when it is in motion and they are represented as F_L and F_D respectively. The magnitude of these forces depends on the relative velocity, v, at which the wing is moving. The residual buoyancy always acts parallel to Z_G. The angle between positive X_B and the relative velocity vector is the angle of attack, α. A schematic showing the forces and velocities on the glider, both during dive-in and dive-up sequence is shown in Fig.4.

Hence the angle of attack α is obtained as in (7).

$$\alpha = tan^{-1}\left(\frac{w}{u}\right) \quad (7)$$

The resultant velocity as a component of surge and heave velocities is given by

$$v = u\,cos\alpha + w\,sin\alpha \quad (8)$$

The corresponding lift and drag forces are given in (9) and (10).

$$F_D = \frac{1}{2}\rho S C_D v|v| \quad (9)$$

$$F_L = \frac{1}{2}\rho S C_L v|v| \quad (10)$$

C_L and C_D are the lift and drag coefficients and can be estimated using computational fluid dynamics method for α ranging from 0° to 90°.

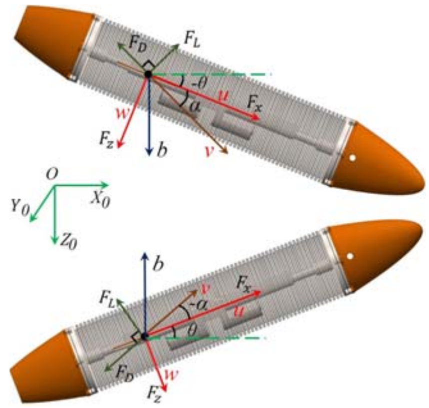


Fig. 4: Forces and velocities on the wing while diving

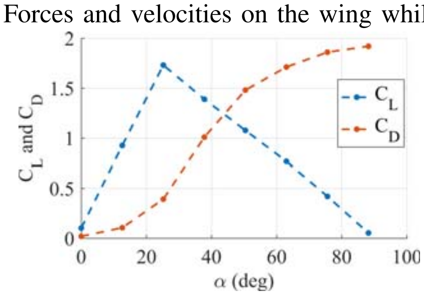


Fig. 5: Variation of C_L and C_D with respect to angle of attack

The variation of these coefficients for the whole range of angle of attack is shown in Fig. 5. This variation is modelled as a look up table and used for simulation. The wing is assumed to be a thin symmetric plate. S is the wing surface area and for the wing shape considered for the prototype, S is obtained as in (11) and α is a scaling factor.

$$S = \frac{3}{4}\sigma^2 l_a l_b \quad (11)$$

The forces F_X and F_Z as components of the lift and drag forces can be represented in matrix form as shown in (12).

$$\begin{bmatrix} F_X \\ F_Z \end{bmatrix} = \begin{bmatrix} -cos\alpha & sin\alpha \\ -sin\alpha & -cos\alpha \end{bmatrix} \begin{bmatrix} F_D \\ F_L \end{bmatrix} \quad (12)$$

The pitching moment due to the offset of wing is given by,

$$M_P = -d\,F_z \quad (13)$$

These forces and moments are external non conservative forces/ moments to the fuselage and they are modelled as parts of input vector to the dynamics of fuselage.

The overall mathematical model of the presented underwater glider can be represented as a block diagram as shown in Fig. 6. The description of all the parameters used from (1)-(13) is given in Table I.

IV. Simulation and Results

Numerical simulations were carried out in *MATLAB* Simulink with different input conditions. The dimensions of fuselage are optimally chosen to make the system neutrally buoyant. The dimensions of wings are decided in a way to maximize the lift to drag ratio. The design variables used in this maximization problem are α and d. CFD based simulations are carried out with the optimized dimensions to estimate the added mass and drag parameters of the fuselage. Initially, few simulations were conducted to test the motion

TABLE I: Description of Parameters

Parameter	Description	Parameter	Description
k	Motor constant	u,w,q	Velocities along surge, heave and pitch directions
g_r	Gear ratio	$\dot{x},\dot{z},\dot{\theta}$	Velocities with respect to O_G
d_r	Rotation to translation ratio	$[x_g,y_g,z_g]$	Location of CoG w.r.to O_B
J	Motor inertia	$[x_b,y_b,z_b]$	Location of CoB w.r.to O_B
L	Motor inductance	$X_{\dot{u}},Z_{\dot{w}},M_{\dot{q}}$	Added mass parameters along u,v and q directions
b_m	Motor damping	X_u,Z_w,M_q	Linear damping coefficients u,v, and q directions
R	Motor coil resistance	$X_{u\|u\|},Z_{w\|w\|},M_{q\|q\|}$	Quadratic damping coefficients along u,v, and q directions
r_b	Radius of bellow	h_1,h_2	Stroke of linear actuators from neutral conditions
ρ	Density of water	v	Relative velocity of wing
g	Acceleration due to gravity	d	Distance of wing from the body center
m	Mass	l_a,l_b	Dimensions of wing
b	Residual buoyancy force	S	Wing surface area
x,z,θ	Position along XG and YG and pitch	C_L,C_D	Lift and drag coefficients

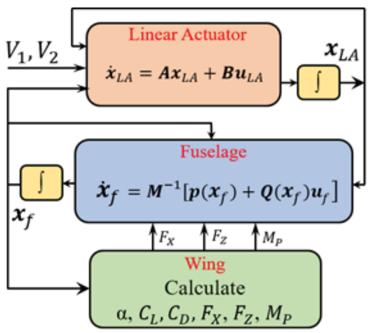
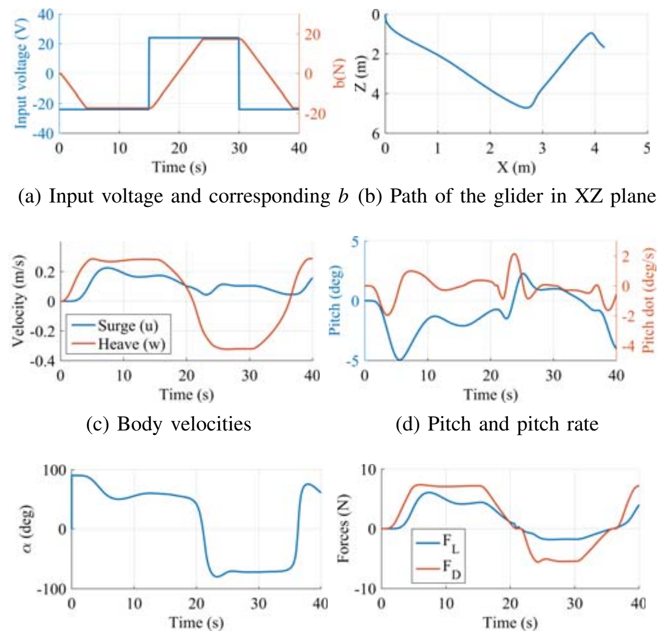


Fig. 6: Block diagram of the overall dynamics

of the fuselage alone without the wings, to understand the behaviour of the system in heave direction. The location of CoG being above the CoB along Z_B helps in achieving roll stability. Later the wing dynamics are also included in the model and simulated. The results of one of the cases of simulation for the whole system is presented in Fig. 7. A pulsed input voltage is given to the system and the corresponding change in the residual buoyancy is shown. The maximum residual buoyancy of the system is +/-19 N. The path traced by the glider in $X-Z$ plane is shown in Fig. 7b and the corresponding variation in angle of attack, pitch and the velocities in body frame are also shown. Multiple such simulations were carried out at different gliding conditions and the results proved the ability of the system to be able to glide underwater.



(a) Input voltage and corresponding b (b) Path of the glider in XZ plane

(c) Body velocities (d) Pitch and pitch rate

(e) Angle of attack (f) Lift and drag forces

Fig. 7: Simulation results showing the performance for a dive-in and dive-out sequence

V. Experimental Setup

An experimental prototype glider has been built as per the optimized dimensions. The prototype at its early stage is designed to understand the behaviour of such gliders with the proposed concept and to analyse the gliding performance. Hence tethers are used for external power and communication with an external PC. It is possible to develop an untethered prototype with in-built autonomy.

The electronic subsystem comprises of user console and the glider console. Commands to the linear actuator and the parameter adjustments can be made from the GUI in the PC. The data and power communications between the user and glider consoles happen through a tether. The glider is equipped with an accelerometer to measure accelerations along surge and heave axis along with pitch measurement. The depth is measured using a pressure sensor and another pressure sensor is used inside the chamber to estimate the overall level of expansion/compression. The information from all these sensors are gathered using a microcontroller and sent to the user console. The linear actuators are controlled using individual motor drivers and the rate of buoyancy change can be controlled using pulse width modulated signals from the microcontroller. The overall mechatronic architecture of the system is shown in Fig. 8.

The glider is 1m long and the diameter of the hull is 0.16 m. The wall thickness of the metallic bellow is chosen in such a way that it can withstand the pressure at 20 m. Suitable provisions are provided to connect the linear actuator to the flanges. The space between the linear actuators and the bellow can be used to house the required electronics. The bellow with flange assembly is sealed with the bellow end-plates and these altogether form the hull of the system. The wings are connected to the hull using hoops and connector plates. The hoops are semicircular rings which will rest on

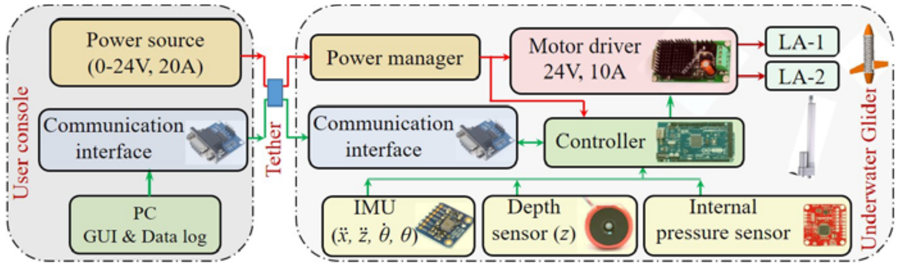


Fig. 8: Architecture of mechatronic system

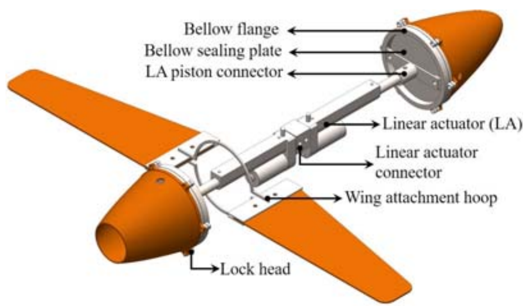
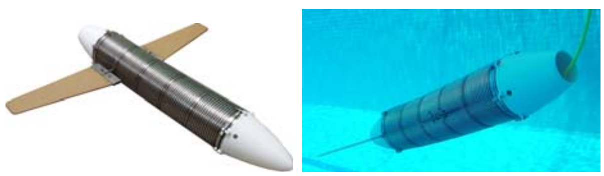


Fig. 9: Internal structure of the glider



(a) Prototype *RoBuoy* (b) Field test

Fig. 10: Pictures of *RoBuoy* prototype and field tests

the trough of the bellow. The wings plates are sandwiched between two hoop arrangements. The wing assembly is modular and the position of the wing with respect to the body can be easily adjusted. The detailed internal structure of the glider is shown in Fig. 9. All parts of the hull, hoop and the wing connector are made of SS316 while the wing is made of acrylic. The nose and tail are 3D printed with ABS plastic. The picture of the experimental prototype is shown in Fig. 10a. The experimental prototype has been developed to prove the concept and a patent has been filed for the overall system [15]. The prototype was successfully tested to dive with open loop commands from the user. The performance of the glider was found to be suitable for shallow water applications. A picture taken during testing of *RoBuoy* is shown in Fig. 10b.

VI. Conclusions

A simple and cost effective underwater glider using 'change of volume' concept is introduced. A prototype *RoBuoy* has been designed with minimal number of parts with all the vital parts concealed. The system has been mathematically modelled and the dimensions has been optimally chosen to maximize the gliding performance. The same has been successfully tested experimentally up to a depth of 5 m. The performance of the system during experiments can be seen in the accompanying video. Further performance studies based on the wing position and hybridizing this glider are also possible.

Acknowledgement

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