Design and Analysis of Cascaded Variable Buoyancy Systems for Selective Underwater Deployment

Thiyagarajan Ranganathan and Asokan Thondiyath
Robotics Laboratory, Department of Engineering Design, Indian Institute of Technology Madras, Chennai, India

Keywords: Variable Buoyancy, Selective Deployment, Bellow with Linear Actuator.

Abstract: Variable Buoyancy systems for selective deployment has been designed and the analysis of dynamics is discussed in this paper. Multiple interconnected VB modules have specific advantages in positioning the payloads like sensors and communication equipment at various depths to collect strategically important subsea data. The design of metallic bellow based Variable Buoyancy Systems (VBS) is presented along with the dynamic analysis of the module. The dimensions of the VB module are optimised to give best performance at the desired depth of operation. Effect of anchoring the module to a base station and cascading multiple modules for deploying at various depths have been studied in detail. Simulation results show that the cascaded VB modules can be successfully deployed for selective applications under various operating conditions.

1 INTRODUCTION

A variable buoyancy system is a device which can change its mass (keeping volume unaltered) or volume (keeping mass unaltered) during its operation, thereby varying the net buoyancy (difference between weight and buoyancy) of the system. When the weight of the system is equal to the buoyancy, the system is Neutrally buoyant and based on the sign of difference between weight and buoyancy, the system is either positively or negatively buoyant. Variable Buoyancy Systems for different underwater applications either for underwater systems or as stand-alone system, is one of the main research interests in the field of underwater vehicles (Sumantr and Teknologi, 2008; Tangirala and Dzielski, 2007; Wen-de Zhao et al., 2010; Worall et al., 2007; Ranganathan et al., 2015; Wu et al., 2011). Such systems dive across the water column by varying the buoyancy and they are used in underwater vehicles to get depth variation during manoeuvres. VBS, being one of the efficient ways to achieve various depths, has potentials much more than just using them as add-ons to underwater vehicles. There may be situations where we need to maintain the depth of a sensor suite underwater to collect information. Depending on the application, sensor suite may need to change the depth at regular intervals to meet specific requirements. Under such circumstances, a VBS can be positioned at the desired depth by anchoring and when required, it can be deployed to the desired depths. Hence VBS can be used as standalone systems which have the ability to achieve required vertical single degree of motion efficiently. However when the depth of operation increases, the length of cable connected to VBS to anchor will increase which may result in couple of issues. First, if the cable is not neutrally buoyant, after a certain length, the self-weight will become higher the maximum positive buoyancy that can be achieved by the VBS and this will lead to system malfunctioning. Secondly, the cable may get entangled and handling the cable will be difficult. In these situations, there is a need for multiple interconnected VBS which will avoid the issues discussed. Furthermore, if the considered scenario is extended in a way that the surrounding environment has to be monitored at various depths simultaneously, the same interconnected VBS can be used. Hence selective deployment can be achieved by having such multiple interconnected modules.

Different types of VBS are available in literature and based on the requirement of selective deployment, a suitable method has to be chosen. Most of variable buoyancy systems use water ballast in which either the weight or volume is changed witha suitable mechanism (Tangirala and Dzielski, 2007; Wende Zhao et al., 2010). (Wu et al., 2014) proposed a ballast based VB mechanism to position the system at a depth. The surrounding water is taken in to increase the mass and vice versa. This may result in corro-

Ranganathan, T. and Thondiyath, A.
Design and Analysis of Cascaded Variable Buoyancy Systems for Selective Underwater Deployment.
DOI: 10.5220/0005979903190326
In *Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2016) - Volume 2*, pages 319-326
ISBN: 978-989-758-198-4

sion of the system when it is operated for longer duration. (Worall et al., 2007) developed a bellow based VB system which uses reservoir with oil and a pump to fill oil in and out of the bellow so that the overall weight of the system is varied. In this case the size of the system becomes large because of the supporting components and the maintenance becomes difficult. Spermaceti oil hypothesis based VB modules are also used in some systems. Paraffin wax with a heating element are used to change the volume of a system (Shibuya and Kawai, 2009). Such response time of such systems are low. A metallic bellow based VB system is reported in (Shibuya and Yoshii, 2013) which uses a peltier element to change the phase of a paraffin wax which can be used to expand and compress the bellow. Some methods use the gas produced by microbes to change volume and thereby achieving variable buoyancy. These systems do not require any external power (Wu et al., 2011).

Considering the need for a controlled buoyancy variation, a VBS with metallic bellows and actuated by linear actuators is discussed in this paper. The necessary variation in buoyancy can be obtained by contracting or expanding the metallic bellow using a suitable linear actuator. A system with a metallic bellow with linear actuator and necessary supporting structures/devices becomes a VB module. Multiple of such modules can be interconnected to selectively deploy at different depths to simultaneously monitor/sense at different depths. The design of a cascaded VB system for selective deployment and intermittent actuation is analysed in the following sections.

2 SYSTEM DESIGN

As discussed in the previous section, selective deployment uses multiple modules cascaded in such a way that each of these modules can be actuated individually or in combination to achieve desired movement or depth. One such cascaded schematic with two modules is shown in figure 1.

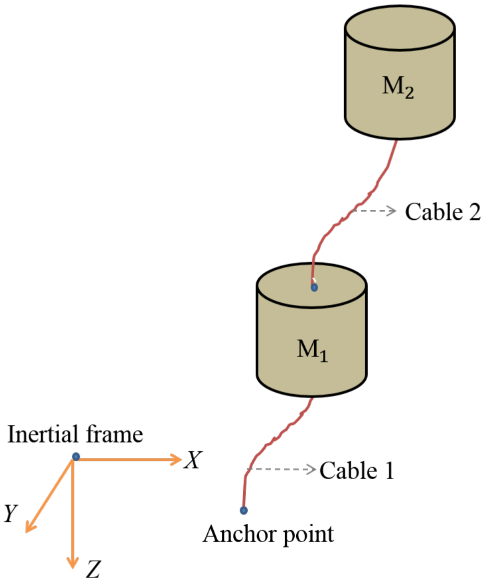
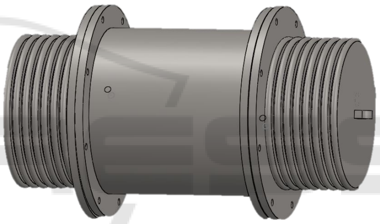
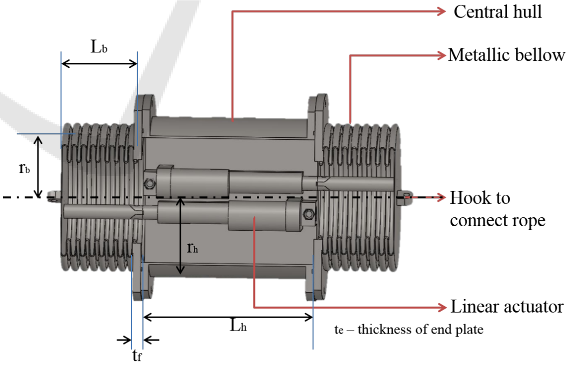


Figure 1: Cascaded modules for selective deployment.



(a) CAD model



(b) Internal view

Figure 2: Conceptual design of a metallic bellow based VB module.

Each of these VB modules is based on the concept of bellow with linear actuators. The conceptual design of a bellow based VB module is shown in figure 2. It has a hull and two bellows. The hull and bellows are connected using flanges with bolts and nuts. The hull provides a platform to hold the linear actuators as well as the electronics required to control the movement of linear actuators. Two linear actuators are used to individually actuate the two bellows. Provisions are made for connectors for power and communication signal transmission. To understand the behaviour of the system, initially, bellow with linear actuator based VBS is modelled mathematically and few open loop simulations are carried out. Then, multiple of such systems are cascaded and simulated.

These modules are designed based on the requirements that they should be able to operate at a particular depth and it is desired that these systems are portable and light weight. To achieve these requirements the dimensions of the module are optimised to minimize the weight of the module and to minimize the force experienced by the end plate of the bellow, subject to constraints on length and neutral buoyancy. Hence with all these objectives, the design parameters like the radius and length of the bellow and the hull were optimized. These dimensions of the system are optimized for it to be operated up to a depth of 10m and are shown below. For a different depth of operation, the dimensions are to be optimized again and the specification of linear actuator will vary.

$$r_h = 110.5mm, r_b = 108.5mm,$$

$$L_h = 130mm, L_b = 193.5mm$$

3 MATHEMATICAL MODEL

The system is assumed to be cylindrical with body fixed coordinate frame $X_0Y_0Z_0$ and the earth-fixed co-ordinate frame is represented as XYZ as shown in figure 3. The six-degrees of Freedom (DoF) dynamics of the underwater system is derived using Newton-Euler equations in body fixed co-ordinate frame as shown in equation (1) (Fossen, 1994; Gianluca Antonelli, 2006).

$$\boldsymbol{\tau} = \boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) \qquad (1)$$

Here, $\boldsymbol{v}$ is the vector representing linear and angular velocites of the system. $\boldsymbol{\eta}$ is the pose vector in earth fixed co-ordinate frame obtained by transferring the body - velocities to velocities in earth frame using $\boldsymbol{J}(\boldsymbol{\eta})$ and integrating the velocities in earth frame. $\boldsymbol{\tau}$ is the external forces and moments vector. $\boldsymbol{M}$ is the matrix comprising of mass and inertia of the system along the principle axes, $\boldsymbol{D}(\mathbf{v})$ is the damping forces and moments matrix, $\boldsymbol{C}(\mathbf{v})$ is the Coriolis and Centripetal forces and moments matrix, and $\boldsymbol{g}(\boldsymbol{\eta})$ is the Restoring forces and moments vector which governs the forces and moments due to difference in Buoyancy (W) and weight (W) of the system and also the position of CoG and Centre of Buoyancy (CoB).

The underwater module will experience force on the end plate due to external hydrodynamic pressure, and internal pressure due to expansion and compression. The spring force of the bellow also influences the dynamics of the actuation of the bellows. The variation of the internal forces as a function of the bellow length variation is plotted in figure 4 .The maximum internal force due to internal pressure for the designed module was found to be +/-350N for an 8% change in length of bellows. The bellow stiffness is taken as 54N/mm. The force on the endplate due to external hydrodynamic pressure will linearly vary with the depth at the rate of 380N/m.

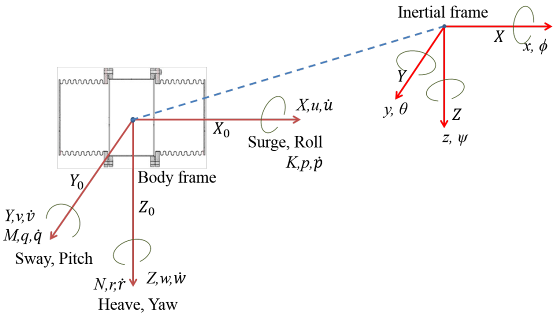


Figure 3: Co-ordinate frame representation.

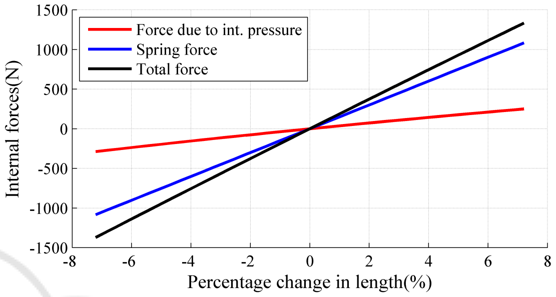


Figure 4: Percentage change in length vs force acting on the endplate.

These forces were also modelled and incorporated in the above discussed mathematical model while analysing the dynamic performance of the module.

3.1 Open Loop Simulation Studies

Simulations are carried out with the mathematical model developed. No external disturbances are considered during the simulation and the pressure variation along the water column is assumed to be uniform. Some studies were carried out to understand the behaviour of the system when it has some initial orientation. When the system is left with an initial orientation of 10° and 20° of roll and pitch respectively, it rolls back to the stable equilibrium position with both becoming 0°. It is because of the restoring moment created due to non-alignment of CoG and CoB. Oscillations are noticed which dies down slowly as shown in figure 5.

When the system is oriented in roll in such a way that the CoG is above the CoB, it is observed that with even small numerical disturbances, it rolls back again to the stable position and oscillates around the stable position. This oscillation dampens down progressively. The net positive buoyancy ‘b’of the system is varied from 0.5N to 3N and the velocity at which the system travels along the water column was studied. It

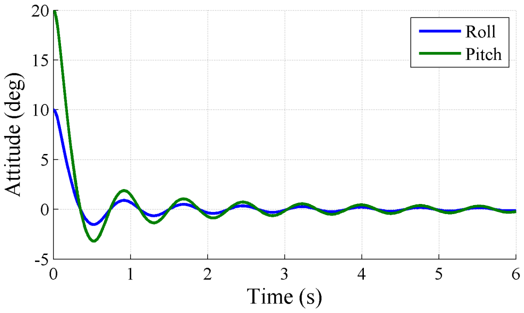


Figure 5: Attitude of the module.

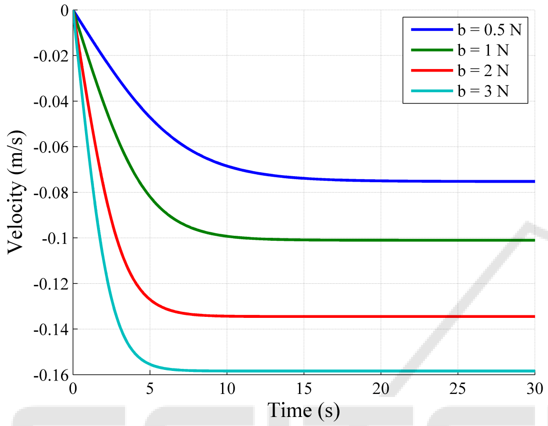
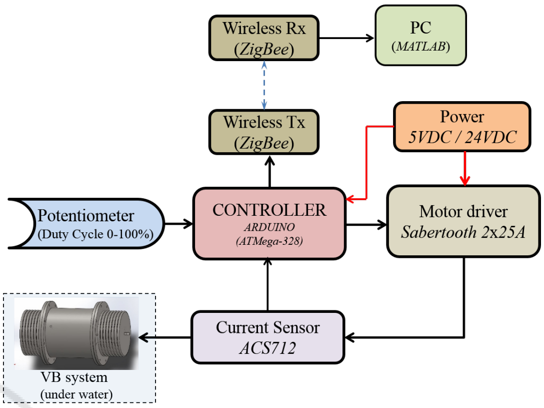
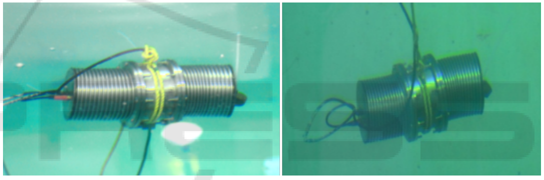


Figure 6: Velocity at various positive buoyancy.

Figure 7: Fabricated prototype.



(a) Schematic of experimental setup.



(b) VB system during operation.

Figure 8: Experimental setup.

was noticed that the system accelerates initially and after some time it starts moving with constant velocity (saturation velocity). At different levels of positive buoyancy, the velocities achieved by the system are shown in 6.

4 EXPERIMENTAL SETUP

The objective of the experimentation is to validate the mathematical model and to understand the power consumed by the system while operating at various depths. To validate the model, a prototype was designed and fabricated based on the dimensions obtained from optimization. The material used for the prototype is stainless steel; figure 7 shows the fabricated system. Two linear actuators are chosen based on the force analysis to expand and compress the bellows. Underwater connectors and cables are used for power and communication signals.

The electrical and electronic setup consists of a controller, motor drivers for linear actuators, and sensors. The role of controller is mainly to get user commands, communicate them to the linear actuator accordingly and collect some vital information from the system, communicate them to the user. A current sensor is used to sense the current consumed in the system during its operation, which can help us estimate the overall power consumed by the system per cycle of operation. The controller will generate Pulse Width Modulated (PWM) signals and send it to motor drivers. A *ZigBee* based wireless communication is used to communicate the parameters like time, current and commanded velocity, instantly to a remote PC in which the data can be recorded and visualised in real time. A 24V 6A DC power source is used to power the entire system and source is stepped down wherever required. The schematic of the experimental setup and some pictures during the operation are shown in figure 8. The entire setup, except the VB module, will act as the ground control station.

4.1 Results and Discussion

Ground experiments were conducted to measure the velocity of the linear actuator at different Duty cycles of PWM. The speed of the linear actuator with respect to PWM duty cycle is shown in figure 9. The

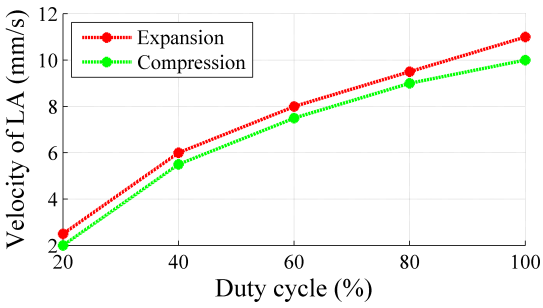


Figure 9: Bench test : Velocity of LA Vs. Duty cycle.

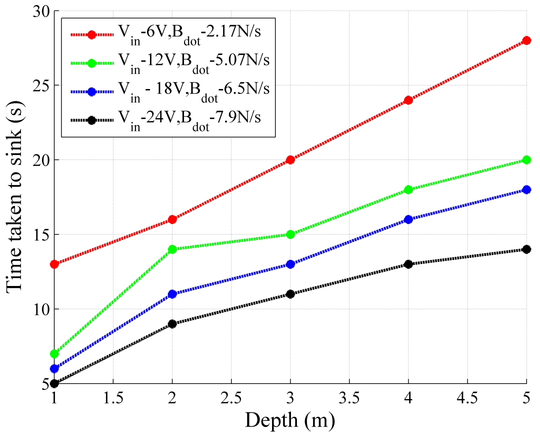
percentage of duty cycle of PWM signal corresponds to the input voltage to the linear actuator at the rate of 0.24V/% of duty cycle. A bench test on the system with different duty cycle input to the system was conducted. It can be seen that the velocity during expansion is faster than the velocity during compression in the bellows.

The following are the results during experiments underwater. Experiments were conducted up to a depth of 5m. The objective of the experiments is to understand the time taken to surface and sink by the system from/to different depths at different rates of change of buoyancy. The rate of change of buoyancy is directly proportional to the velocity of the linear actuator which is commanded by the input voltage to the linear actuator. Experiments were repeated six times at each depth and the mean time taken by the system to sink/surface to a particular depth with different duty cycle is shown in figure 10.

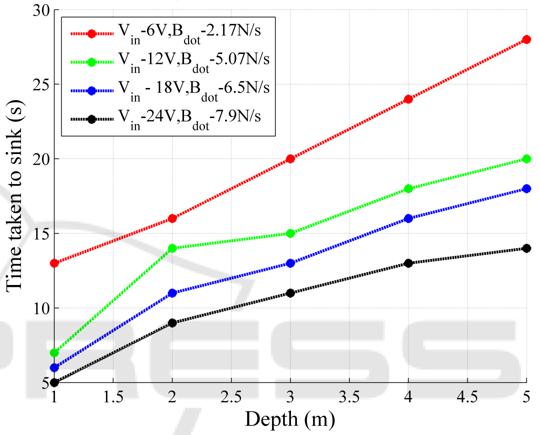
It can be observed that the time taken to surface is slower than the time taken to sink to the same depth. This is mainly due to the external pressure variations during sinking and surfacing. The experimental results are compared with the simulation results for a particular buoyancy variation. The experimental and simulation results of time taken to sink and surface at 12V and 24V are shown in figure 11.

Simultaneously, the current consumed for surfacing and sinking to a depth by expanding or contracting is logged. It was found that the expansion from a depth consume more current than compression initially since the linear actuator has to overcome the force due to external pressure to expand. On the other hand, the force required to compress is comparatively lesser since the external pressure itself aids in compression.

5 ANCHORED AND CASCADED SYSTEMS



(a) Time taken to sink.



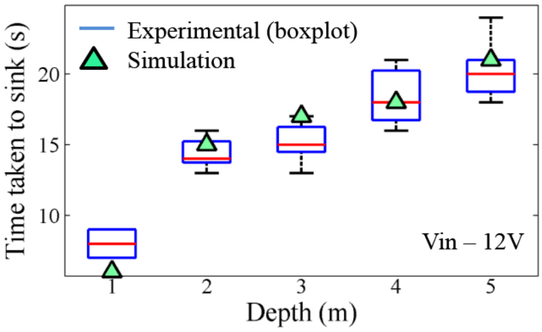
(b) Time taken to surface.

Figure 10: Time taken to sink and surface at different rate of change of buoyancy.

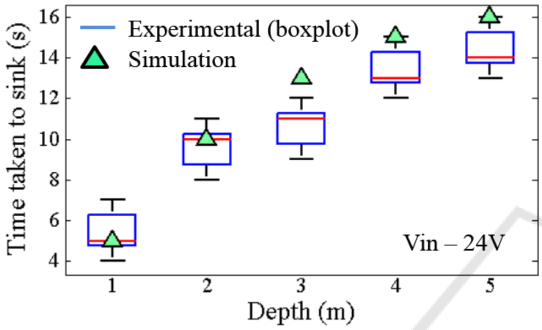
Simulation studies were conducted to understand the behaviour of the system when the VB module is anchored at a particular depth as shown in figure 12. The point to which the cable is connected to the system is *P* and the length of the cable is *L*. For this simulation, the cable length is assumed to be 3m, anchoring point *A* is [0,0,0] and the initial point at which the system is positioned is [1,0.5,-1] with respect to the inertial frame. The behaviour when the module travel along Z is shown in figure 13. It can be seen from the plot that it the system travels up and it oscillates when the cable is stretched completely. The dynamics of the cable is not considered in this simulation.

Now another module is cascaded on top of the anchored module as shown in figure 1. Initially the buoyancy of both the modules are kept neutral. The cascaded module is made positively buoyant by 1N after 50th second of simulation.

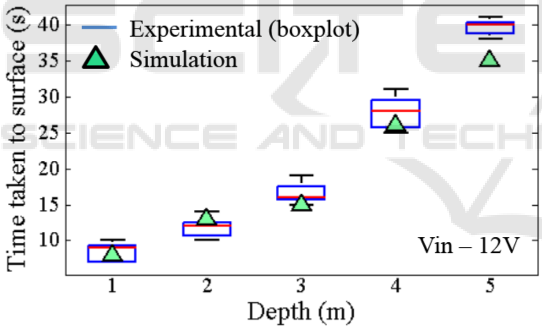
The modules are initially located at [0.5,0,-0.5] and [1,0,-0.5] and the point to which the first module is anchored is at [0,0,0] with respect to the earth frame. Cable lengths are 2m and 5m for the first and



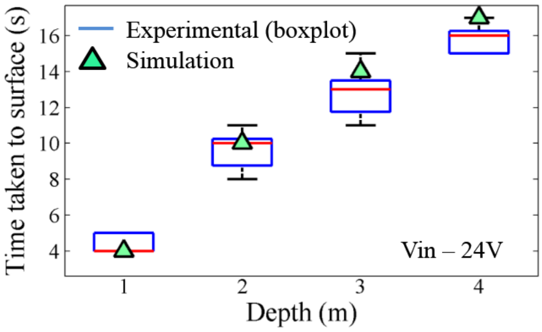
(a) Time taken to sink at V_{in}=12V.



(b) Time taken to sink at V_{in}=24V.

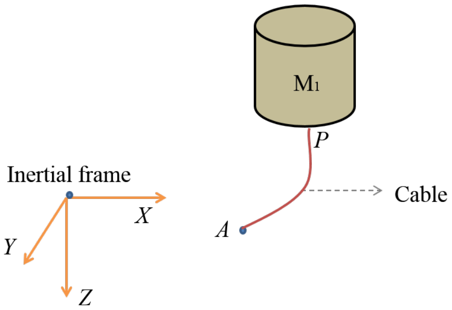


(c) Time taken to surface at V_{in}=12V.

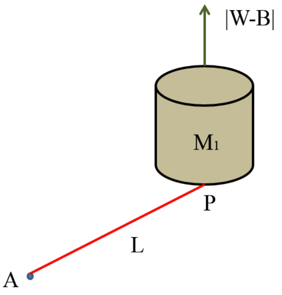


(d) Time taken to surface at V_{in}=24V.

Figure 11: Comparison of experimental and simulation results.



(a) Initial position.



(b) When cable is stretched.

Figure 12: An anchored system.

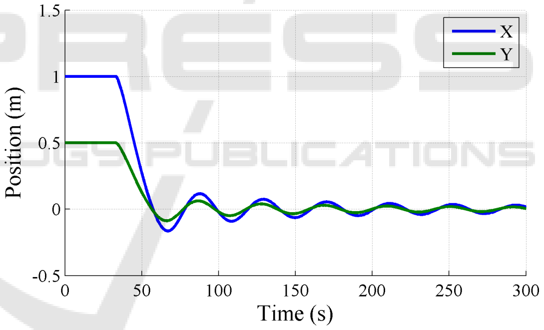


Figure 13: Variation in XY position of the VB module when anchored.

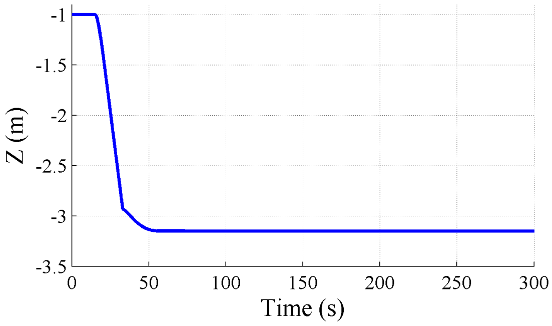
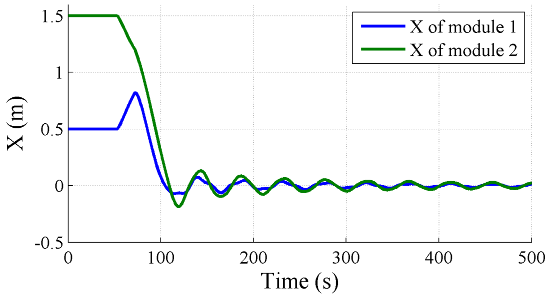
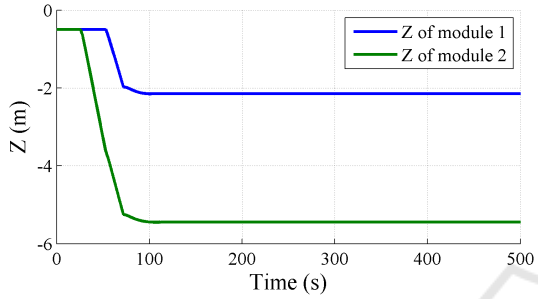


Figure 14: Variation in Z of an anchored module.

second modules respectively. It can be seen that, as the second system moves up, when the cable is completely stretched, the positive buoyancy of cascaded



(a) Variation of X for both modules.



(b) Variation of Z for both modules.

Figure 15: Variation of position of both the modules.

module acts on the anchored module which influences the anchored module also to travel up. Both the modules oscillate with the oscillations of cascaded module influencing the oscillations of anchored module. The travel of both the modules along the water column can be seen in figure 15.

6 SUMMARY OF THE WORK

A metallic bellow based variable buoyancy system is designed with dimensions optimally chosen based on system requirements. The system is mathematically modelled and the basic simulation studies shows that the system is capable of diving to the desired depth and surface by expanding or compressing the linear actuator. The simulation studies also showed that the system with some orientation in roll and pitch because of any external disturbance will re-orient itself back because of the restoring force created due to positions of CoG and CoB. The terminal velocities of the system at different positive buoyancies were studied and it was found that at 3N positive buoyancy, the system travels with a velocity of 0.32m/s. Experimental results show that the mathematical model closely approximates the real system. The power consumption study at different velocities of linear actuator shows that, at maximum tested depth of 5m, with the maximum speed of linear actuator, the system consumes an instantaneous power of about 24W. With the mathematical model, further simulations are carried out by anchoring single system at a depth and by cascading multiple such systems. The simulation studies show that, when the system is positively buoyant, irrespective of the initial position at which it is, because of the cable getting taught, it oscillates around the anchor point. When the system is at neutrally buoyant state, the system remains at the same position unless there is external disturbance acting on it.

7 CONCLUSIONS

The study reveals that the system is well suited for the selective deployment applications and the ability of them to be used as a single degree of freedom system to have motion along heave. The study also shows that the velocity of the system can also be controlled by controlling the rate of change of buoyancy. Multiple of such systems with individual depth control can be cascaded and these systems can be deployed at different depths in the designed range.

Some issues were noticed while experiments like, maintaining the symmetry of the bellows which resulted in an unwanted tilt in the system. Also, since two linear actuators were used, positioning them maintaining the centre of actuation of both the bellows is not possible. This can be avoided by using a single vertical bellow based VBS. Open loop response of the system is studied and further, the system can be analyzed with a model based closed loop control strategy to precisely control the depth using suitable sensing. The depth control capabilities and performances can be analyzed which may explore various other applications.

REFERENCES

Fossen, T. I. (1994). *Guidance and Control of Ocean Vehicles*.

Gianluca Antonelli (2006). *Underwater Robots*.

Ranganathan, T., Pattery, J., and Thondiyath, A. (2015). Design and analysis of cable-connected metallic bellows as Variable Buoyancy Modules. In *2015 IEEE Underwater Technology (UT)*, pages 1–5. IEEE.

Shibuya, K. and Kawai, K. (2009). Development of a new buoyancy control device for underwater vehicles inspired by the sperm whale hypothesis. *Advanced Robotics*, 23(7-8):831–846.

Shibuya, K. and Yoshii, S. (2013). New Volume Change Mechanism Using Metal Bellows for Buoyancy Control Device of Underwater Robots. *International Scholarly Research Notices Robotics*, 2013:1–7.

Sumantr, B. and Teknologi, U. (2008). Development of Variable Ballast Mechanism for Depth Positioning of Spherical URV. In *International Symposium on Information Technology (ITSim)*, pages 1–6, Kuala Lumpur, Malaysia. IEEE.

Tangirala, S. and Dzielski, J. (2007). A Variable Buoyancy Control System for a Large AUV. *IEEE Journal of Oceanic Engineering*, 32(4):762–771.

Wen-de Zhao, Xu, J.-a., and Zhang, M.-j. (2010). A Variable Buoyancy System for Long Cruising Range AUV Wen-de Zhao, Jian-an Xu and Ming-jun Zhang. In *Internation Conference on Computer, Mechatronics, Control and Electronic Engineering*, pages 585–588.

Worall, M., Jamieson, A. J., Holford, A., and Neilson, R. D. (2007). A variable buoyancy system for deep ocean vehicles. In *OCEANS 2007 - Europe*, volume 44, pages 1–6. IEEE.

Wu, J., Liu, J., and Xu, H. (2014). A variable buoyancy system and a recovery system developed for a deep-sea AUV Qianlong I. In *Oceans 2014 - Taipei*, pages 1–4. IEEE.

Wu, P. K., Fitzgerald, L. a., Biffinger, J. C., Spargo, B. J., Houston, B. H., Bucaro, J. a., and Ringeisen, B. R. (2011). Zero-power autonomous buoyancy system controlled by microbial gas production. *The Review of scientific instruments*, 82(5):055108.