Multi-operated HIL Test Bench for Testing Underwater Robot's Buoyancy Variation System

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Abstract

Nowadays underwater gliders have become to play a vital role in ocean exploration and allow to obtain the valuable information about underwater environment. The traditional approach to the development of such vehicles requires a thorough design of each subsystem and conducting a number of expensive full scale tests for validation the accuracy of connections between these subsystems. However, present requirements to cost-effective development of underwater vehicles need the development of a reliable sampling and testing platform that allows the conducting a preliminary design of components and systems (hardware and software) of the vehicle, its simulation and finally testing and verification of missions. This paper describes the development of the HIL test bench for underwater applications. Paper discuses some advantages of HIL methodology provides a brief overview of buoyancy variation systems. In this paper we focused on hydraulic part of the developed test bench and its architecture, environment and tools. Some obtained results of several buoyancy variation systems testing are described in this paper. These results have allowed us to estimate the most efficient design of the buoyancy variation system. The main contribution of this work is to present a powerful tool for engineers to find hidden errors in underwater gliders development process and to improve the integration between glider's subsystems by gaining insights into their operation and dynamics.

KEYWORDS: underwater glider; buoyancy; hardware-in-the loop; hydraulic; simulation

1.1. Introduction

Existing autonomous underwater devices range from simple data gathering devices to highly sophisticated autonomous unmanned vehicles (AUV) and nowadays they are widely used for subsea exploration. They represent a powerful frame for different sensors, sonars, cameras and other equipment that help to provide the science data such as temperature, salinity/conductivity and currents. These data are the function of depth and vertical variation of these parameters is very important and plays an extremely significant role in ocean dynamics. As a matter of fact, such task does not necessarily assume a precision underwater vehicle delivering and as a result does not require a propulsion system. In these cases, just steering is enough. This fact has become an initial point for developing a relatively new class of vehicle nowadays known as underwater gliders [1-4] that have changed the way of ocean observation.

Underwater gliders have no propulsion system except their ability of changing their buoyancy that enables them to gradual descent and ascent. Their fixed wings convert this vertical motion into inclined. It leads to ‘saw-tooth’ trajectory of their motion. During these saw-tooth evolutions, the glider’s sensors and data acquisition systems are constantly taking and recording samples of the ocean’s conductivity, temperature and depth. When the vehicle is at the surface, positioning is obtained via GPS and communication between the vehicle and the home base is via satellite. Therefore, underwater gliders are believed to provide a powerful platform for ocean exploration and fill in the gap left by existing powered AUVs and remotely operated vehicles (ROV).

Design process of an underwater glider, its further refinement and certification requires a large bulk of engineering data such as aggregates characteristics, kinematic relations, knowledge about flow ripples, vibrations, systems speed-of-response and others. Only theoretical approach for glider simulation can not be applied for describing control units as they have in effect nonlinear characteristics, frictions, and noises which are complex to be considered theoretically. As to traditional laboratory static tests of underwater gliders, they in fact focus only on functionalities of a particular component or systems and do not provide significant information about dynamics of a whole glider. Another approach was developed in paper [5] where dynamic tests of AUV were performed with minimum risks related to the security and costs. These tests covered more tests conditions in comparison with static tests. However, such full scale test besides each components manufacturing and assembling also require robot ballasting in the water, qualified personnel and divers. All of these makes full scale tests extremely expensive [6]. Herewith there is a risk of losing the whole robot during full size tests. Additionally, there are quite often situations when a controlled object is at the stage of engineering while a control unit already exists.

With this in mind we draw attention to hardware-in-the-loop tests (HIL) that involve both hardware and software components and at the same time dynamic or behavioral conditions. The problems solved by hardware-in-the-loop test benches are detailed described in paper [7].

The HIL approach was previously applied to a number of underwater vehicles' components and systems [8-11]. However, our literature analysis showed the HIL technology does not widespread in underwater glider developing. There is no significant information how to design HIL test bench for buoyancy variation system characteristics investigation and how to provide a good accuracy of these tests. The purpose of this paper is to present an approach to assist control engineers in process of developing of underwater gliders, improving the integration between such subsystems as buoyancy, power management, navigation, sensing and others.

1.2. Multi-operated HIL test bench

The process of multi-operated HIL test bench developing applied to underwater gliders according to [12] consists of the construction following environments, tools and modelling:

Underwater glider's kinematics: the glider considered here has an ellipsoid body with fixed wings and tail, ballast control and controlled internal moving mass. The glider centre of buoyancy (CB) is coincident with the ellipsoid centre.

There are two reference frames for describing the kinematics of the underwater glider (Figure). The first one is inertial, non-rotating reference frame $O\xi\eta\zeta$. $O\xi$ axis aligned with horizon line, $O\eta$ axis aligned with gravity force direction, $O\zeta$ lies in the horizon plane perpendicular to gravity. The second reference frame is the body-fixed frame, $CBxyz$. Its *CBx* axis lies along the long axis of the vehicle (positive in the direction of glider's nose). *CBy* axis lies in the plane of the wings and *CBz* axis lies in the orthogonal to the wings plane as shown in Figure.

The orientation of the glider is calculated by means of the rotation matrix *R*. *R* maps vectors expressed with respect to the body frame into inertial frame coordinates using Bryant angles - φ_1 , φ_2 , φ_3 . The position of the glider, $\overline{b}$, is the vector from the origin of the inertial frame to the origin of the body frame as shown in Figure 1.

The vehicle moves with translational velocity $\overline{v} = (\overline{v_x}, \overline{v_y}, \overline{v_z})^T$ relative to the inertial frame and angular velocity $\overline{\omega} = (\overline{\omega_x}, \overline{\omega_y}, \overline{\omega_z})^T$, both expressed in the body frame.

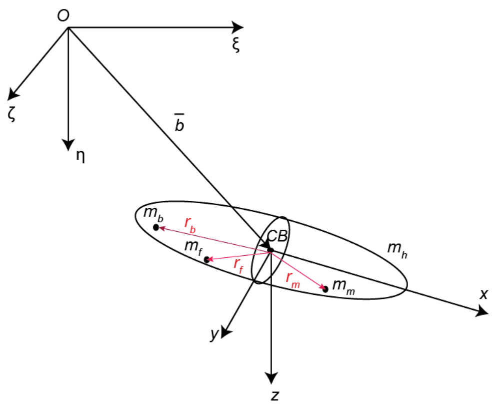


Figure 1: Glider position and orientation variables

Underwater glider's dynamics: The dynamic model is based on Lagrangian equation of motion and includes the most important elements of glider dynamics such as glider configuration and its external geometry, the forces of gravity and buoyancy, hydrodynamic forces (lift, drag and sideforce), the effects of added mass and inertia due to motion in a dense fluid, and the control of moving internal and ballast masses. We have not taken into account the geometry of AUV and real disposition of the buoyancy variation system in an explicit form as well as hydrofoil, roll, trim and pitch angles of the underwater robot.

The Lagrangian equation of motion uses energies in the system instead of forces. Consequently, the kinetic energy of the whole glider can be expressed as a sum of kinetic energies of transitional and rotational motions:

$$T = \frac{m_f \left(\dot{\bar{r}}_f^{(0)}\right)^2}{2} + \frac{m_m \left(\dot{\bar{r}}_m^{(0)}\right)^2}{2} + \frac{m_b \left(\dot{\bar{r}}_b^{(0)}\right)^2}{2} + \frac{m_h \left(\dot{\bar{r}}_h^{(0)}\right)^2}{2} + \frac{\overline{\omega^T} \cdot J_h \cdot \bar{\omega}}{2}, \tag{1}$$

where m_f is a mass of non-movable glider's elements; m_m is a movable point mass; m_b is a variable ballast mass; m_h is a uniformly distributed hull mass; r_f is a positon vector from CB to centre of gravity (CG); r_m is a position vector from CB to m_m; r_b is a position vector from CB to m_b; r_h is a position vector from CB to m_h; J_h is an inertia tensor of glider's hull

Notice that the total mass of the glider is the sum of four masses:

$$m_v = m_h + m_f + m_m + m_b(t). \tag{2}$$

Let denote *m* as the mass of the fluid displaced by the vehicle. Then the net buoyancy, m_0, is a difference between vehicle mass and mass of displaced fluid *m*:

$$m_0 = m_v - m \tag{3}$$

As a result, the vehicle is negatively/positively buoyant if m_0 is positive/negative.

Hydrodynamic forces such as lift force, Yi, drag force, Xi, and moment, M_{yi} can be expresses in the body-fixed reference frame as:

$$Y_i = C_{yi}\frac{\rho_f \llbracket (V \rrbracket_1^T)^{\frac{2}{3}} v_i^2}{2} + C_{xi}\frac{\rho_f A_0 v_i^2}{2}, \tag{4}$$

where C_{yi} is the lift force coefficient in the corresponding plane; ρ_f is a fluid density;

V_1 is the volume of the glider's hull; A_0 is a cross sectional of the vehicle.

$$X_1 = C_{xi}\frac{\rho_f \llbracket (V \rrbracket_1^T)^{\frac{2}{3}} v_i^2}{2} + C_x\frac{\rho_f A_0 v_i^2}{2}, \tag{5}$$

where C_{xi} is the drag force coefficient in the corresponding plane.

$$M_{y1} = m_{y1}\frac{\rho_f v_i^2}{2} V_1^T, \tag{6}$$

where m_{yi} is the sideforce coefficient in the corresponding plane.

Modelling different ballast systems: Buoyancy variation system of underwater robots is the key system that determines the accuracy of its motion, submersion capability, acoustic properties, reliability and resource. Before designing our test bench we analysed the existing designs of buoyancy variation systems. All of them are thoroughly described in paper [13]. To chose the most efficient construction among existing we set a number of the most significant initial conditions: immersion depth, its velocity, time period between emersion and immersion. Almost all existing underwater robots are known to have maximum immersion depth 1000 m., robot's velocity is not more than 1.5 m/s, time period between emersion and immersion is 1 min. These parameters have been taken as initial data for HIL test bench design. Based on the conducted analysis we have chosen only two of them (Figures 2 and 3) as others do not provide necessary immersion depth and/or

have increased noise and necessity of sufficient expensive materials.

Construction in Figure 2 uses bi-directional pump to transfer oil between external and internal bladders. This fluid transport leads to change the robot integral volume as well as buoyant force. As a result, robot either descent or ascent.

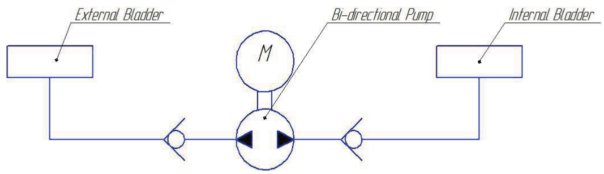


Figure 2: Schematic construction “a”

Construction in Figure 3 uses uni-directional pump, flow directional switching valve. The working principle of this construction is similar to construction “a”. Fluid transportation also leads to volumetric change of the robot.

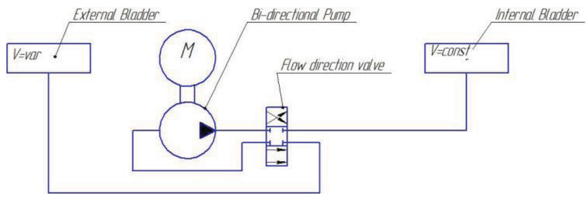


Figure 3: Schematic construction “b”

Underwater glider's control system: The glider receives the information about desired depth, H_{dez} from an operator and apply an output to the buoyancy variation system. The depth can be controlled with help of pressure transducer. The relationship between depth and ballast mass is relatively simple and linear. As a result, it allowed us to implement a PID controller. The depth control system is shown schematically in Figure 4.

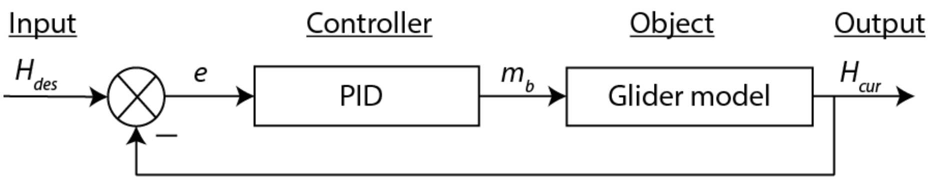


Figure 4: Block diagram of the PID depth controller

Where *e* is the depth error; buoyancy variation output; K_P is a proportional gain; K_I is an integral gain; K_D is a derivative gain.

PID controller also can be implemented for vehicle's velocity control. Velocity is obtained from the equation of motion [18] for the buoyancy engine with respect to volumetric displacement:

$$m \cdot \ddot{z} = \pm \rho_f g \Delta V - \frac{\rho_f A_0 C_d}{2} \dot{z}|\dot{z}| \tag{7}$$

where *m* is the structural mass of the robot; $\ddot{z}$ is the acceleration of the robot in vertical direction; *g* is the acceleration due to gravity; ΔV is the volume changing; $\dot{z}$ is the velocity of the robot in vertical direction.

To control the vehicle's direction, it was used a slide-mode control, presented by Figure 5 and also used in [12]. The velocity and direction controller work together where, depending of the current direction's value, it is possible to increase or decrease the vehicle's velocity.

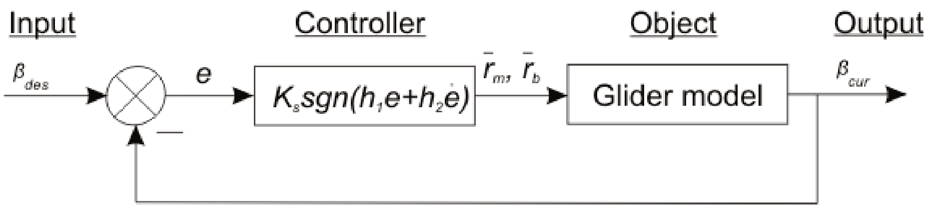


Figure 5: Block diagram of he slide-mode direction controller

Where β_{des} is a desired value of the sideslip angle; β_{cur} is a current value of the sideslip angle; K_s is Positive and negative limits used over the thruster output; h_1 is the error gain; h_2 is the error rate gain.

Data acquisition system: HIL test bench require a variety of analog and digital interfaces to interact with full-scale aggregates. We have chosen a NI Single Board RIO controller to built the data acquisition system. This controller is very popular in embedded applications. It has high performances converters combined with onboard processing for counter/timer functionality and low-latency data transfers to the real-time processor. Like other real time operating systems, it supports multiple tasks and preemptive scheduling. It makes this controller very powerful and reliable for HIL test system applications.

Developed test bench has a measurement system. It allows us to measure static pressure in 3 points, pressure oscillations in 3 points, gear pump vibration, gear's angular velocity and noise of the system by means of acoustic camera Norsonic 848. The data acquisition and processing program written by means of NI LabView software.

Real time framework: it bases on an object oriented real time framework that allows to interface and generate code from a dynamic model developed directly in NI LabView. **Development environment:** Environment parameters such as water temperature, currents, waves are taken into account by the model of glider's dynamic developed in LabView software.

Hardware in the loop simulation environment: The main purposes of the developed HIL test bench are:

- monitoring of working processes occurs in full-scale buoyancy variation system;

- refinement and debugging of the control systems;

- providing the Iron Bird testing of the robot full-scale components combined with its control system aimed to developing the robot energy efficient design and components configuration

Therefore, developed HIL test bench provides the possibility of investigation of constructions "a" and "b". The circuit diagram of developed HIL test bench is shown in Figure 6.

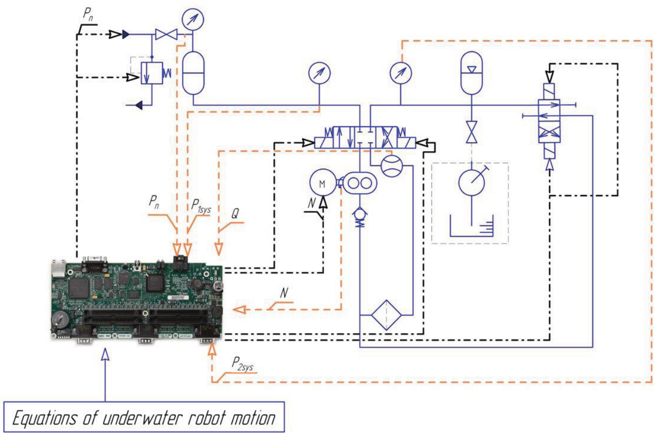
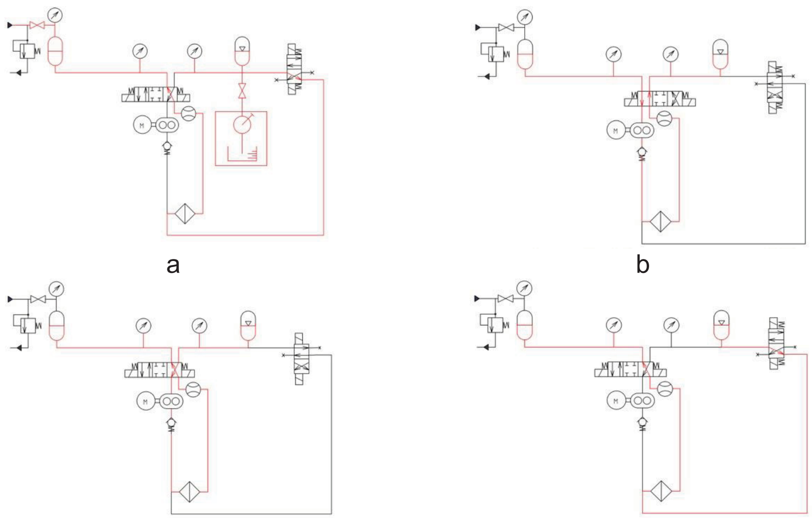


Figure 6: The circuit diagram of the SSAU HIL bench.

The working principles of the developed HIL test bench are described in Figure 7.



a b

c d

Figure 7: The hydraulic circuit diagram working principles
a – the filling of hydro and pneumatic accumulators by means of hand pump; b – fluid transferring from external bladder to internal bladder (descent simulation); c – fluid drain from internal bladder to external (ascent simulation); d – fluid drain from internal bladder to external (emergency ascent simulation)

The developed HIL test bench (Figure 8) consists of two main interdependent systems. The first one is the depth simulation hydraulic system. It includes a hydraulic power station (not shown), hydraulic accumulator AndyMark PM25R-35F-1001, valves VD4-W1/30and pressure transducers PCB Piezotronics. Depth simulation system is required for the real working conditions simulation that is necessary for a buoyancy variation system correct work. This system is a singularity of the developed test bench. The second main system is the directly hydraulic buoyancy variation system, which in our case consists of a gear pump Duplomatic 1P 1,6 R 11N, an electromotor, a hydropneumatic accumulator Hydac 12/05 3N, directional control valves Rexroth 4 WE 6 E62/EG24N9K4/ZV and Caproni RH06201, a filter HMM281F10XNR, pressure and accelerometer transducers, encoder, pipes and fittings. This system is needed for simulation of mass or volume changing of the whole robot. It leads to either descent or ascent of the robot.

The versatility of developed test bench is that its design can be changed rapidly. Besides the control system is versatile and can be modified for different types of buoyancy driven robots as well as all hydraulic components.

The main characteristics are:

working fluid: oil AMG-10 (PQ Hydraulic Fluid 4328);

working temperature: 4-25 ^{0}C;

pressure: up to 10 MPa;

volumetric flow rate: up to 1 l/min;

Figure 8: A general view of developed test bench

1.3. Results and discussion

By applying the equations described earlier to each construction we obtained their dynamics for further evaluation. Our initial results have shown that two investigated buoyancy variation systems constructions are approximately equal. Figure 9 shows the changing of volume displacement (a), changing of vehicle depth (b) and its velocity (c). The parameters ΔV , H_{cur}, are taken from the test bench and send to the mathematical model to estimate the robot dynamics. As can be seen the design “a” is better than design “b” because of increased robot’s dynamics.

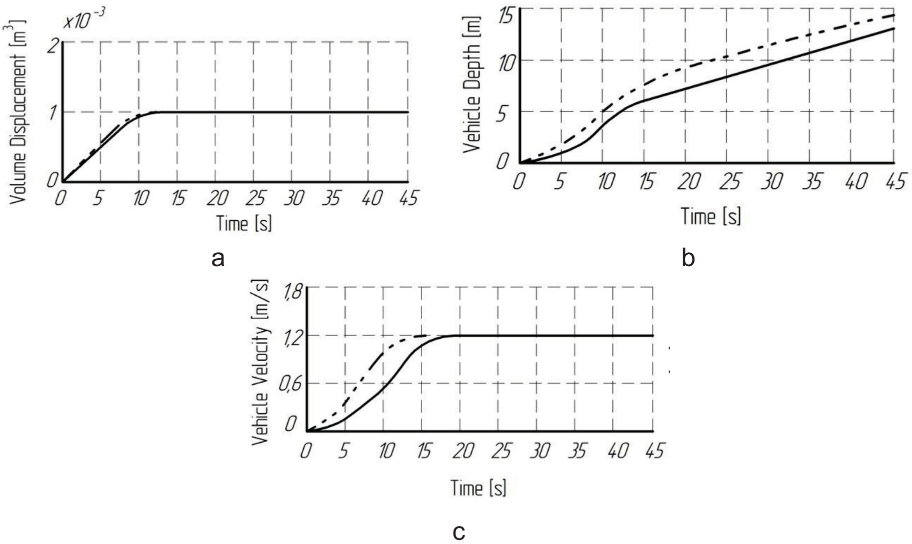


Figure 9: Buoyancy variation system characteristic curves
– - - – design “a”; —— design “b”

1.4. Further investigations

We are planning to thoroughly investigate the acoustic performances of each presented here buoyancy variation systems as well as their vibration to localize the noise sources in each construction. Also we are planning to investigate transient processes in the hydraulic systems. Our further works will be also focused on control system refinement and optimizing.

1.5. Conclusion

The HIL test bench for iron bird testing of the underwater robot's hydraulic buoyancy variation systems is described in this paper. Developed HIL test bench is able to significantly simplify the design, simulation and refinement processes. It gives the possibility to control an amount of pumped fluid and the accuracy of robot motion.

Besides increased informational content, HIL test benches have some other advantages:

- there is no risk of loosing the robot during tests in comparison with the real tests;
- possibility of aggregates rapid changing;
- there are no special requirements for environment;
- there is no need in diving equipment and personnel carrying out the tests under water.

1.6. Acknowledgments

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