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A small variable buoyancy system for underwater vehicles

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Abstract. An improved variable buoyancy system (VBS) has been developed for small underwater vehicles. This paper presents the system design, controller design and the underwater experiments. Based on the first-generation prototype, we developed a new mechanical device which has lighter weight and better waterproof performance. A PD controller combined with tracking differentiator (TD) have been adopted to achieve stable depth maintenance. Experimental results show that the improved VBS achieved a good performance. During the 120s experiment period, the VBS only moved 5mm.

1. Introduction

Underwater vehicles often work in different depth. In many cases, they should maintain a certain position to finish their tasks, which can be accomplished through the cooperation of multiple propellers. However, this will consume a lot of energy since the propellers should keep working to ensure the stabilize of underwater vehicles. In order to solve these problems, an active VBS is proposed. It is an independent system which can adjust the buoyancy of the whole equipment. And it offers a low cost, low battery consumption solution compared to propellers. Therefore, the VBS is useful for unmanned underwater vehicles such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs).

We can adjust the volume or change the weight to adjust the buoyancy of an underwater vehicle. Therefore, the variable buoyancy system has two basic forms: variable ballast type and variable volume type [1, 2]. Variable ballast type is generally used in manned vehicles or large AUVs. It changes the volume of water in the body to adjust the whole weight. In traditional submersibles, water is pumped out by high pressure gas. However, water is pumped out by water pumps in some other systems, such as the SEAHORSE [3], SHINKAI6500 and OCEANLAB [4]. Due to the compactness of this method, it seems more popular in small AUVs. In variable volume type, the volume change is generally achieved by using oil sac, pistons or air sac. COPEX [5] developed by National Ocean Technology Center uses the mechanical method, its piston driven by a gear motor injects hydraulic oil into the sac to change the overall volume of the body. Different from COPEX, SEAWING AUV [6] adjusts the oil sac volume by hydraulic pump. Besides, a method based on volume varying in medium's phase transition, is used in the SLOCUM glider [7].

Because of the large weight and volume of variable ballast type of VBS, it is often used in submarines, and large unmanned AUVs. In contrast, variable volume type of VBS is more suitable for small AUVs due to its compactness and simplicity. A small improved VBS for underwater vehicles which is updated from the first-generation prototype [8] is presented in this paper. It not only achieves good waterproof performance, but also further reduces the weight of VBS. And in this improved VBS, the oil flows automatically into the sac by the high pressure in the accumulator. It solved the problems



faced by the traditional devices, such as controlling the buoyancy at shallow depth. And at the same time, it will provide the VBS an emergency response capacity when a power failure occurs.

2. Development of the VBS

Based on the first-generation prototype, we developed a new mechanical device which has lighter weight and better waterproof performance. Besides, in this paper, the oil flows automatically into the sac by the high pressure in the accumulator instead of external water. As a result, the problems like controlling the buoyancy at shallow depth can be easily solved. The VBS to be introduced is divided into three parts, including mechanical part, hydraulic drive and control circuit.

2.1. Development of mechanical part

Due to some shortcomings of the first-generation prototype, we developed the second version which can not only achieve good waterproof performance, but also can further reduce the weight. The improved VBS outlook picture is shown in **Figure 1**. From the picture, we can see that the cabin of the VBS is only sealed one end and the other end is closed which not only makes installation easier, but also improved waterproof performance since it only needs to seal one part instead of two. In order to avoid the use of traditional soft oil sac which will cause a serious problem that the oil can't return to the accumulator, we designed a hard-outer-wall oil sac as shown in **Figure 1**.

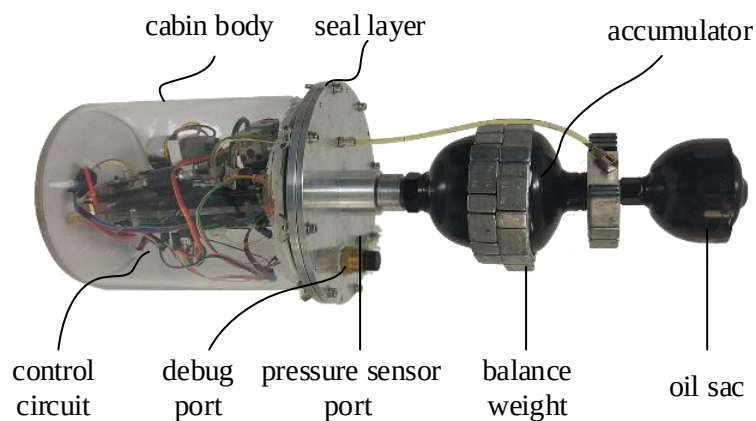


Figure 1. The improved VBS outlook picture.

Its overall parameter is only 4kg in weight, 160mm in diameter and 450mm in height. It is 0.5 times compare with the first-generation prototype which makes the improved VBS more competitive and portable.

2.2. Development of hydraulic drive

At present, most variable volume type of VBS use hydraulic method in which oil is pumped into the external oil sac by unidirectional pump and squeezed out by the pressure of the external water. However, it will be hard to control the buoyancy at shallow depth because of the low water pressure. In this improved VBS, like the first-generation prototype, the oil flows automatically into the sac by the high pressure in the accumulator. It solved the problems faced by the traditional devices, such as controlling the buoyancy at shallow depth. And at the same time, it will provide the VBS an emergency response capacity when a power failure occurs. In addition, although it uses unidirectional pump, it can still control the directional valve to quickly switch between the two conditions of injecting oil and ejecting oil through controlling the directional valve without frequent start and stop of the pump. Due to the complete hydraulic solution, there is no moving part except for the pump and valve, all key parts use static seals which have higher sealing reliability and a longer life compared to the mechanical method.

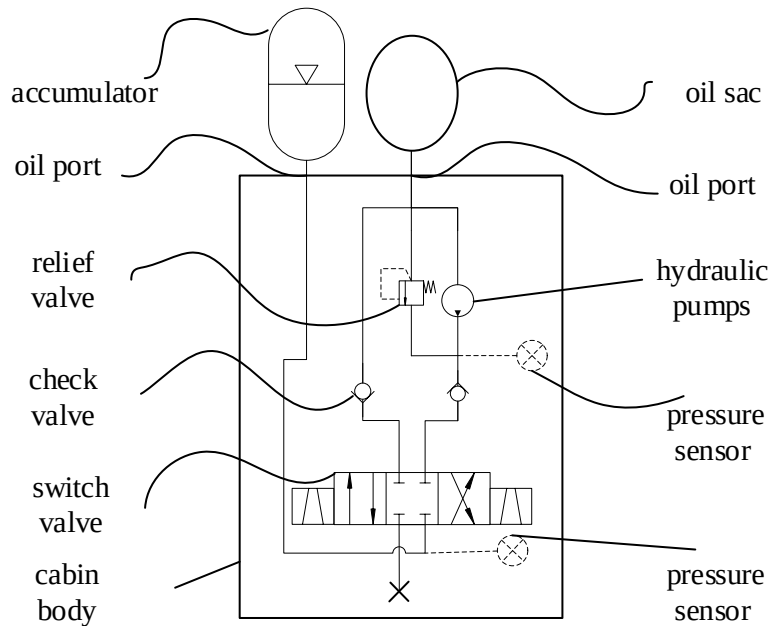


Figure 2. The hydraulic unit schematic.

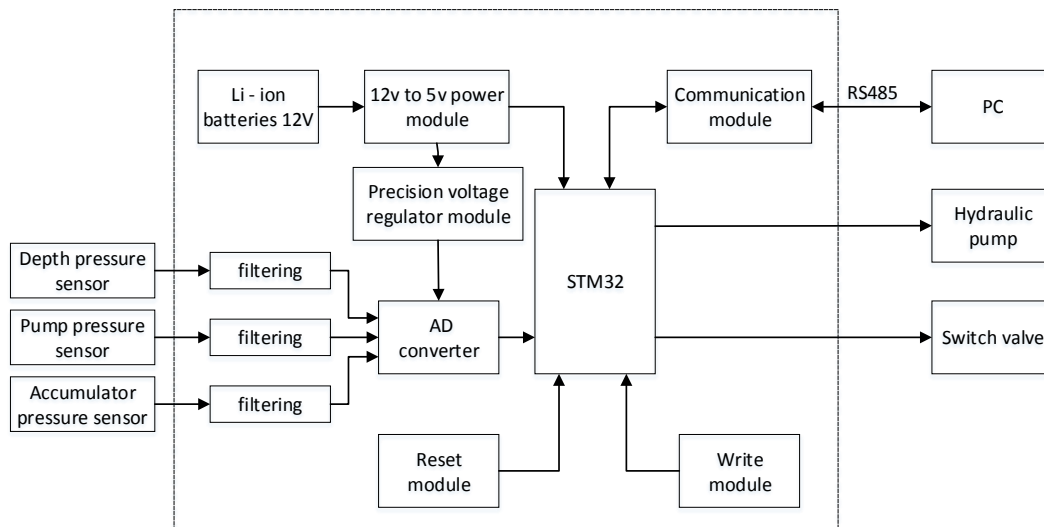


Figure 3. The control circuit structure.

The hydraulic system schematic designed in this paper shows in figure 2. Three states of the switch valve represent the three states of the system including inflating, deflating and maintaining the oil sac. First, when the valve in the figure 2. moves to the left, the hydraulic pump is connected to the accumulator. With the help of high pressure pump, the oil will extract from the external sac and charge into the accumulator through the check valve. And with the help of check valve, oil can't flow back from the high-pressure accumulator if the pump pressure drops under certain conditions. As a result of oil sac decreases in volume, the VBS will generate a downward acceleration. When the valve comes to the middle position, the accumulator channel is blocked. At this time, no matter if the dump is running or not, the volume of external sac will not change. Finally, when the valve moves to the right, the oil sac is connected to the accumulator. In this situation, the oil flows automatically into the sac by the high pressure in the accumulator. As a result of increased volume of oil sac, the VBS will get an upward acceleration.

2.3. Development of electronic circuit

The control circuit structure is shown in figure 3. We used a 3200mah of 12V Li-ion battery as VBS's power supply and with the help of 12V to 5V power module and precision voltage regulator module, we got a 5V regulated power output for AD converter which translate the signal of pressure sensors to digital signal for STM32. The communication between PC and STM32 has two options: Bluetooth and RS485. The Bluetooth is used for simplify the debug process and when it comes to long-distance communication, RS485 is the best choice.

3. Development of Depth-Controller

For small AUVs, there are some difficulties to achieve stable depth maintenance, such as the cooperation of multi-propellers and chatter effect. However, as for the VBS, it is much easier to achieve stable depth maintenance. In this paper, a PD controller combined with tracking differentiator(TD) have been developed to achieve high robustness against the noise.

3.1. System modelling

For the accumulator, it is assumed that the temperature is constant in any condition. According to the ideal gas state equation, the model is shown as:

$$P_{pre}V_{all} = P(V_{all} - V_r) \quad (1)$$

Where P_{pre} and P represent the accumulator pressure of pre-charged and the current pressure; V_{all} is the volume of whole accumulator; V_r is the reduced volume of oil sac.

In order to simplify the physical model, we assume that the downward is positive direction and it only can move in the depth direction. Then, we have following formulas.

$$\begin{aligned} mg - \rho V_t g - kv &= ma \\ mg &= \rho V_m g \\ \Delta V &= V_t - V_m \\ a &= -\frac{\rho g}{m} \Delta V - \frac{k}{m} v \end{aligned} \quad (2)$$

Where V_m is the volume of oil sac at the suspension state and V_t is the volume of oil sac. Considering that the whole device does not move fast in water, the water resistance force of the device can be simplified as $F_r = -kv$. Derivatives for the above formula:

$$\dot{a} = -\frac{\rho g}{m} \Delta \dot{V} - \frac{k}{m} \dot{v} \quad (3)$$

Where $\Delta \dot{V}$ is the derivative of changed volume of oil sac. Assume $\alpha = \rho g/m$, $\beta = k/m$, $\Delta \dot{V} = u$, we have $\dot{a} = -\alpha u - \beta \dot{v}$. Thus, the state space model of system can be described as follow:

$$\begin{bmatrix} \dot{y} \\ \dot{v} \\ \dot{a} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{k}{m} \end{bmatrix} \begin{bmatrix} y \\ v \\ a \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\frac{\rho g}{m} \end{bmatrix} u \quad (4)$$

Where $u = \Delta \dot{V}$, represents the rate of flow and is numerically equal to q , it is the control variable for this system.

However, the calculation of q is very complicated. To simplify the situation, we ignore the valve leakage and turbulence. The flow rate can get from orifice flow formula:

$$q = K_L A \sqrt{P_A - P_B} \quad (5)$$

Where q is the flow rate, K_L is pipe-resistance coefficient, A is equivalent sectional area and P_A, P_B is the pressure of accumulator and oil sac respectively. Because the switch valve only has three states, we used Pulse-Width Modulation(PWM) mode in which we control the open time of valve to achieve an equivalent continuous control. Assume DR is the duty ratio, we can get:

$$\Delta \dot{V} = -DR \cdot q \quad (6)$$

3.2. Depth-Controller

Adaptive fuzzy, Bang-bang control [9] and PD control [10] has been utilized in VBS's depth control. Compared to traditional PID controller, in this paper, a PD controller combined with tracking

differentiator (TD) have been developed to achieve high robustness against the noise. A discrete version of TD [11] is given as follows:

$$\begin{cases} x_1(k+1) = x_1(k) + Tx_2(k) \\ x_2(k+1) = x_2(k) + Tfst[x_1(k), x_2(k), u(k), r, h] \end{cases} \quad (7)$$

Where $u(k)$ is the input signal at k ; x_1 is the tracking signal of the input signal; x_2 is the approximate differential signal of the tracking signal; T is the sampling period; h is the filter factor; r is the tracking speed factor.

The fst function is described as follows:

$$fst = \begin{cases} -ra/\delta & , |a| \leq \delta \\ -rsgn(a) & , |a| > \delta \end{cases} \quad (8)$$

Where:

$$a = \begin{cases} x_2 + y/h & , |y| \leq \delta_0 \\ x_2 + 0.5(a_0 - \delta)sgn(y) & , |y| > \delta_0 \end{cases}$$

$$\delta = rh, \quad \delta_0 = \delta h, \quad y = x_0 - u + hx_2, \quad a_0 = \sqrt{\delta^2 + 8r|y|}$$

The enhanced PD controller's structure is shown in the **Figure 4**. In order to avoid the chattering effect a dead-zone is added into the system. There is no overshoot to track the original signal and it shows strong anti-noise ability.

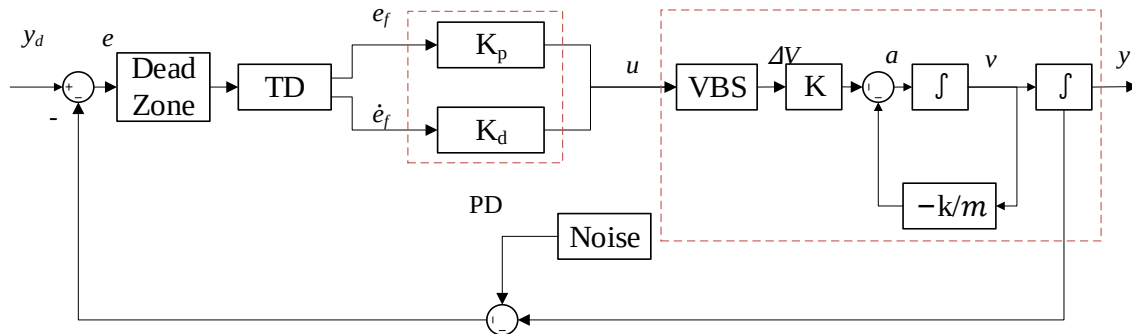


Figure 4. Block diagram of control system model.

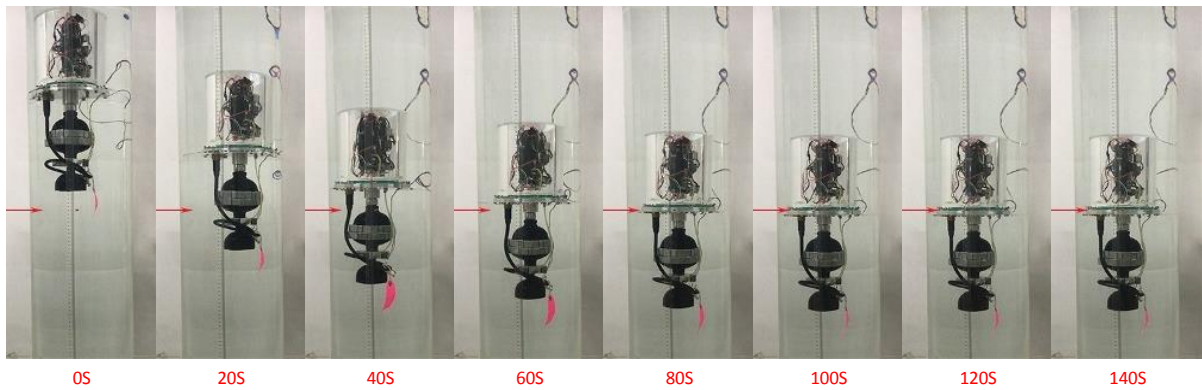


Figure 5. The process of the experiment.

4. Experiments

In order to verify the reliability of the improved VBS, we conducted an underwater experiment. Figure 5 shows the process of the experiment. There are 8 pictures, and the interval between two pictures is 20s. Figure 6 shows the performance of depth controller during the underwater experiment.

Through the analysis of experiment data, we can see that compared to the propeller, the VBS can achieve higher stability. During the experiment, the VBS only moved 5mm after it reached the target depth. At the same time, the improved VBS can achieve lower energy consumption which is able to

work for about 4 hours continuously when battery is fully charged. It means that the average energy consumption is only 8w.

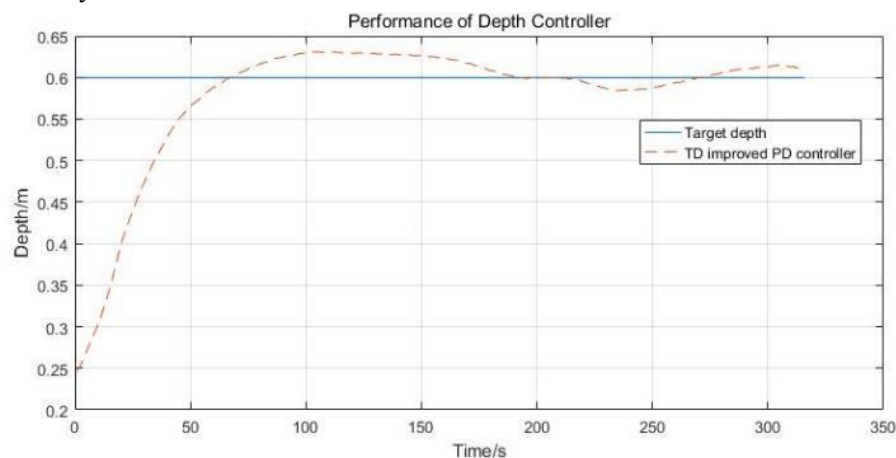


Figure 6. Performance of depth controller.

5. Conclusions

A small improved VBS for underwater vehicles which is updated from the first-generation prototype is presented in this paper. It takes the advantage of accumulator, the oil flows automatically into the oil sac by its high pressure. It not only achieves good waterproof performance, but also further reduces the weight of VBS. At the same time, it is easily modified to meet different user requirements. Then, we developed a new PD controller for the VBS, and it performs well in multiple underwater experiments.

Acknowledgments

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