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Analysis of Balance-control Mechanism for Mini Underwater Vehicle Based on Magic Ball with Metamorphic Characteristics

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Abstract: As the short distance between their centers of gravity and buoyancy, the mini underwater vehicles will become unstable and lose balance attitude easily under external interference which may affect their normal operation. A new balance-control mechanism for mini underwater vehicle is proposed in this study. The study describes the working principle of the balance-control mechanism, introduces the balance control method for rolling and pitching motion and further analyzes the mechanical structure and the metamorphic mechanism characteristics of the ball. The kinematics analysis of the magic ball is given and the relationship between the volume of the magic ball and time is obtained when actuating speed is a constant. The result suggests that the balance-control mechanism which has quick response to external interference can change the local buoyancy of whole underwater vehicle system effectively. The simulation results of rolling motion verify the feasibility of the balancing mechanism which lay the foundation for later research.

Key words: Underwater vehicle, balance control, metamorphic mechanism, rolling motion, pitching motion

INTRODUCTION

The mini underwater vehicles have become an important tool for various underwater tasks with so many advantages including their small size, low cost, safety and flexibility (Gan *et al*., 2006). However, because of the short distance between their centers of gravity and buoyancy, the mini underwater vehicles become difficult to control and lose its balancing attitude easily under the effect of external interference, such as fast-flowing currents, surges, storms. The stability of the vehicles may become worse with the influence of reacting force when the manipulator holds a payload. For these above issues, the underwater vehicles need a balancing device to help them restore balance. The previous control system is usually very complex since it utilizes controlling thread paddle or propeller frequently to restore moment (Liu *et al*., 2009). The fact that the thrusters are installed on both sides of the vehicle and consequently the distance between the central axis of the vehicle become short makes the recovery torque smaller and postpone the attitude adjusting response. For these reasons, the researchers have proposed some new balancing devices. Several researchers have proposed sliding mode junction control method to achieve the balance compensation mechanism for vehicle pitching motion control (Li and Liu, 2009) but the method can not solve the vehicle rolling motion problem; some researchers have put forward a solution that change the position of movable float blocks to control the position of the center of buoyancy with respect to the center of gravity and then result in different righting moment (Sakagami *et al*., 2010). This study presents a new balancing mechanism which can transfer the gas position and then changing the local buoyancy of entire underwater vehicle to generate the righting moment for vehicle balancing attitude adjusting.

METHODS

The outline of this paper is the following: Firstly, the balancing mechanism model of the underwater vehicle and its balance principle for different motion of the underwater vehicle are introduced. Secondly, analyze the magic ball's mathematical relationship and then establish the model of floating ball through three-dimensional software. Thirdly, kinematics analysis of the magic ball is conducted to verify the performance of the proposed balancing mechanism. The last, based on the results of the above sections, the simulation analysis of the underwater vehicle with balancing mechanism is described and the results show that the balancing mechanism is promising for use in balance adjusting of underwater vehicle.

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UNDERWATER VEHICLE WITH BALANCING MECHANISM

To illustrate the motion of underwater vehicle, the establishment of the fixed coordinate system and moving coordinate system. The origin of moving coordinate system is at the center of gravity of the vehicle (Li, 1999), as depicted in Fig. 1. Center of gravity G_0 (x_0, y_0, z_0) and center of buoyancy F_0 (x_{F0}, y_{F0}, z_{F0}) are coincident in the x-y plane. The distance of the center of buoyancy and the center of gravity in the z-axis direction is the standard center distance, also known as the met centric height B0 which can help the vehicle to generate restoring moment in rolling and pitching motion. For the six DOF underwater vehicles, the six components of motion can be defined as advance and retreat, lateral, lift, roll, pitch and yaw. The balancing-control mechanism presented in this study is developed to help the mini underwater vehicles to restore balance quickly in the rolling or pitching motion.

There are four same floating balls which can be filled with gas evenly distributed on both sides of the vehicle, as presented in Fig. 2. The four floating balls connect with a reservoir bag by four gas pipes and the gas can flow freely between the reservoir bag and four floating balls. The reservoir bag is fixed in the bottom of the vehicle.

Both sides of the floating balls can expand and shrink according to the roll angle and pitch angle of the underwater vehicle, resulting in buoyancy difference and buoyancy moment which can help the underwater vehicle to restore balance. The roll angle and pitch angle are measured by a full 360° range clinometer. The expansion and shrinkage of floating balls are accomplished by the mechanism motion inside the balls. When the mechanism unfolds, the floating ball expands with the gas flows to it under the pressure of water. While the mechanism close, the gas under the pressure of water will flow to the other floating balls that needs to be expanded through the reservoir bag and the floating balls themselves will shrink. The transfer of the gas position is realized in the process of mechanism's unfolding and closing. The following section introduces the rationale of the proposed balance-control mechanism working in the three different states of the underwater vehicle.

Balanced attitude: The whole underwater vehicle is in balancing attitude when it is in normal operation. At this time, the four floating balls show half expansion and half shrinkage. The gas uniformly filled in the four floating balls. The values of buoyancy difference and buoyancy moment of the four floating balls are zero.

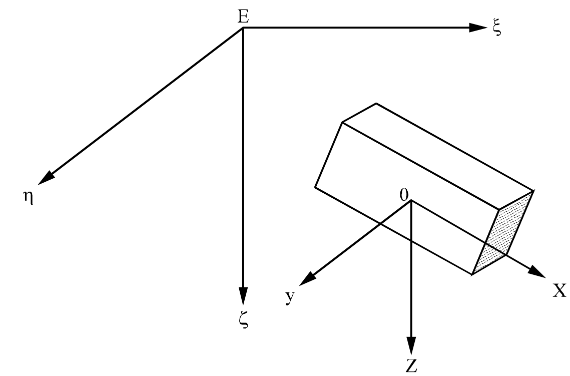

Fig. 1: Fixed and moving coordinate systems for underwater vehicle

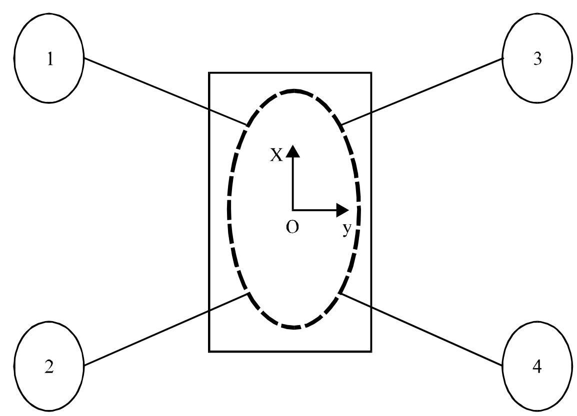

Fig. 2: Balancing-control mechanism model of underwater vehicle

Rolling motion: When the underwater vehicle is in rolling motion affected by external interference in y-axis direction, the floating ball 3, 4 and 1, 2 expand and shrink alternately. If the balancing control system requires a counterclockwise restoring moment in the center of y-axis, the floating ball 3, 4 expand and the floating ball 1, 2 shrink. The gas in floating ball 1, 2 under the pressure of water will flow to floating ball 3, 4 which have much smaller gas density. The buoyancy difference between the left and right side in the floating balls produce floating moment to prevent the external interference moment from continuing to break the balance of underwater vehicle and help the vehicle to return to the balanced attitude quickly in order to achieve the whole system balancing purpose.

Pitching motion: When the underwater vehicle is in pitching motion affected by external interference in x-axis direction, the floating ball 1, 3 and 2, 4 expand and shrink alternately. If the balancing control system requires a counterclockwise restoring moment in the center of x-axis, the floating ball 1, 3 expand and the floating ball 2, 4 shrink. The working principle is similar to rolling motion control.

In addition, the vehicle's control system can change the expansion and shrinkage level of the four floating balls according to the different sizes of buoyancy difference during the process of underwater vehicle's attitude adjustment, thereby generating a variety of buoyancy difference and restoring moment to deal with different levels of external interference.

STRUCTURE ANALYSIS OF THE FLOATING BALL

The expansible and shrinkable floating ball of the proposed balance-control mechanism in this study consists of the magic ball which can unfold and close and the airbag which cover on the magic ball. Due to the influence of water pressure, the pressure is different between internal and external of the ball when it is in the water. To achieve the complete expansion of the ball and to control the flow direction of the gas are both too difficult if you just rely on the gas flow. The magic ball can support the floating ball and control the gas flow direction through the magic ball's unfolding and closing. As depicted in Fig. 3a, the three same annular-fitting are working in three spaces. The magic ball is made up of three same annular-fitting that are assembled by a parallelogram mechanism consisting of connecting rods and movable blocks. The airbag is wrapped in the outermost layer of the movable blocks, so that the entire ball is in a closed state.

The annular-fitting consists of 8-component units with head-to-tail connection in 45° evenly distribution and can stretch and contract, as shown in Fig. 4. Each component unit consists of two pairs of scissors mechanism and two movable blocks. Each scissors mechanism is made up two connecting rods and each of which has three revolving joints. The three revolving joints are triangular distribution, one in the center and the other two locate in both ends of the connecting rod. The intersection of the center connecting lines of two movable blocks of each component unit is at the center of floating ball of the magic ball. For any configuration of annular-fitting, the angle between two adjacent center connecting lines remains the same and only the diameter of the magic ball changes. The Fig. 3 shows that the unfolding (A), semi closing (B), closing (C) process of the magic ball, i.e., corresponding the three states of the floating ball: Fully expanded state, half expansion and half shrinkage state and fully shrinkage state.

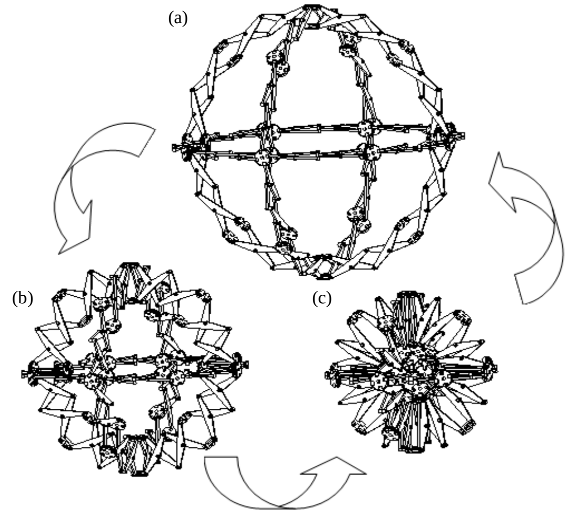

Fig. 3(a-c): Changing process of the magic ball configuration, (a) Magic ball fully unfolding, (b) Magic ball semi-closing and (c) Magic ball fully closing

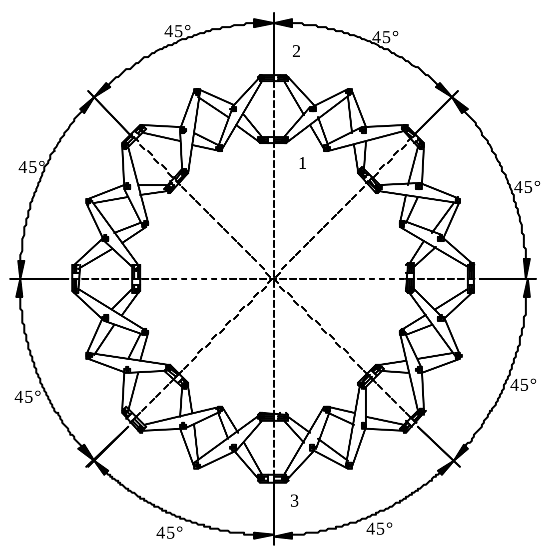

Fig. 4: Annular-fitting with ring-evenly distributed 8 component units

From the perspective of theory of mechanism, the magic ball belongs to multi-pole and multi-loop space mechanism. When the magic ball is fully unfolding or closing, its DOF is 0 while during the unfolding and closing, the DOF is 1. The shape of the magic ball remains unchanged and the size keeps changing in the movement. So the magic ball is a class of boundary metamorphic mechanism with changing configuration state (Dai *et al*., 2002). Inspired by some of the existing research (Dai and Jones, 1999; Dai and Zhang, 2000), comparing with traditional mechanism and the total number of all effective links or the number of DOF of the metamorphic mechanism change as it moves from one configuration to another. When the distance between two movable blocks of any scissors mechanism is minimum or maximum, the magic ball is in steady state and its DOF is 0. In both cases, the magic ball moves to the limit position in unidirectional movement and the motion of the magic ball fully unfolds or closes. These two steady states correspond to fully shrinkable and fully expandable state of the floating ball which can enhance the stability and reliability of the balancing mechanism itself. In the meanwhile, the floating ball shape can remain the same when the vehicle is in the attitude balance control after external interference. When magic ball is in the course of expanding and closing, the DOF is 1, so the movement control of the mechanism is easy to realize.

Then, analyze one of the component units through mathematical modeling, as described in Fig. 5.

In isosceles triangle, ΔBDC:

$$\angle DBC+2\angle BDC = 180 \quad (1)$$

In triangle ΔADC:

$$\angle ACD+\angle ADC+\angle DAC = 180 \quad (2)$$

$$\angle ACD = \angle BCD-\angle BCF = \angle BDC-\angle\beta \quad (3)$$

$$\angle ADC = \angle BDC+\angle ADB = \angle BDC+\angle DAC+\angle\beta \quad (4)$$

Conclusion from Eq. 1 to 4:

$$2\angle DAC = \angle DBC \quad (5)$$

In triangle ΔBDO:

$$\angle BDO+\angle DBO+\angle BOD = 180 \quad (6)$$

$$\angle BDO = 180-\angle ADB = 180-(\angle DAC+\angle\beta) \quad (7)$$

$$\angle DBO = \frac{1}{2}\angle DBC = \angle DAC \quad (8)$$

$$\angle BOD = \frac{1}{4}\angle\alpha \quad (9)$$

Conclusion from Eq. 5 to 9, $\angle\alpha = 4\angle\beta = 45$.

In triangle ΔABC, $\angle\beta = 11.25°$, assuming the length of the connecting rod is 50 mm, i.e., AC = 50 mm and then establish the mode of magic ball (A), as presented in Fig. 4.

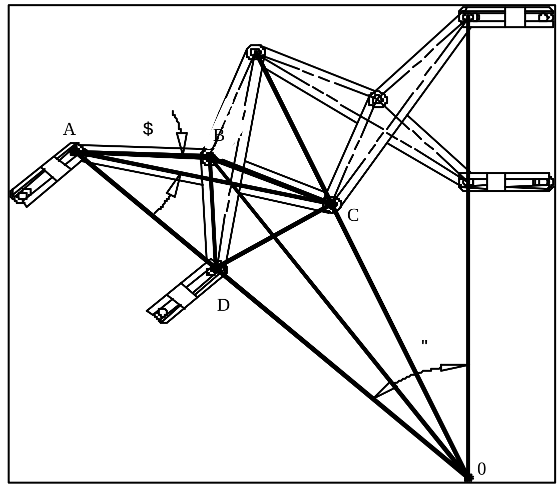

Fig. 5: Geometric diagram of one component unit of the magic ball

The magic ball's unfolding and closing is driven by the relative movement of two movable blocks (1, 2) of any scissors mechanism, its movement using screw drive in the study. Movable block 1 is fixed at one end of the screw rod and the movable block 2 moves along the screw rod as a screw nut. Only a short route by the back and forth movement of the movable block 2 can achieve the rapid unfolding and closing of magic ball. Therefore, the underwater vehicle can respond quickly to external interference.

RESULTS AND DISCUSSION

As described in this study, a balancing-control mechanism for mini underwater vehicle is proposed. The proposed balancing mechanism is based on volume changing of the floating balls and the position of the gas transferring inside the floating balls, then generating buoyancy difference and righting moment on both sides or front and back of the underwater vehicle. Volume changing of floating ball is accomplished by using the unfolding and closing of the magic ball. Through the kinematics simulation analysis of the magic ball in the following sections, the proposed balancing mechanism has rapid response characteristics and the response time is 1.1 sec. Compared the relationship of roll angle with time of the two cases with the same external interference, the roll angle (7.2°) of the vehicle with balancing mechanism is smaller than the roll angle (14.8°) of the vehicle without balancing mechanism and the time of restoring the balance attitude is reduced from 14.3-6.8 sec.

The result is that the proposed balancing mechanism is able to help the vehicle restore the balance attitude during external interference.

KINEMATICS SIMULATION AND ANALYSIS OF THE MAGIC BALL

The balancing mechanism can change the magnitude of local buoyancy of the vehicle system and generate the restoring moment for underwater vehicle through the expansion and closure of floating ball when the vehicle's attitude changes after external interference effect. Therefore, it is required the speed of balancing mechanism in response to external interference should be very quick and that demands that the magic ball must be closed and unfolded quickly. Here, the magic ball's unfolding and closing is achieved and the relative movements of the movable block 1 and 2.

The kinematics analysis of the magic ball by PRO/E mechanism analysis module. Assuming the movable block 2 is uniform motion and the speed is 25 mm sec^{-1}, then the route of movable block 2 with respect to movable block 1 can be obtained, as presented in Table 1. From the Table 1, the minimum distance of the two movable blocks is 20.72 mm and the magic ball fully unfolds at this moment. While the maximum distance of two movable blocks is 48.21 mm, the magic ball fully closes at this time. In the entire movement process, the route of movable block 2 is 27.48 mm and the time is 1.1 sec.

As describe in Fig. 4, the distance between movable block 2 and 3 is regarded as the magic ball's diameter D. Table 1 shows that the change of relative position of movable block 1 and 2, the displacement of movable block 2, the magic ball's diameter and the volume in unfolding-closing process of the magic ball. The following are assumed, movable block 2 maximum displacement X_{max}, magic ball's maximum volume V_{max}, magic ball's minimum volume V_{min}. From Table 1, X_{max} = 27.48 mm, V_{max} = 13.23×10^6 mm^3, V_{min} = 2.52×10^6 mm^3, V_{max}/V_{min} = 5.25 this means that the volume will be increased 5.25 times when the magic ball changes from the closed to the unfolded process. Therefore, the rapid process from unfolding to closing and a wide range change of the volume of the magic ball by just the back and forth movement in a short route of the movable block 2.

After using the method of curve fitting to fit volume-time data, it can be seen that the root-mean-square error is minimal when using quadratic polynomial fitting, as depicted in Fig. 6. The Eq. 10 is the fitted relationship between Volume of the magic ball and time:

$$V(x) = -1937x^2-171500x+13240000 \quad (10)$$

Assume V_L and V_R represent the left and right volume of the floating balls. The right side of the floating ball is regarded as the research object, x refers to the route of the movable block 2 and ΔV means the different volume V_R-V_L.

$$\Delta V = V_R-V_L = -15874x^2-343000x+10720000 \quad (11)$$

When x = 17.34 mm, the volume of the left and right two floating balls equals, ΔV is 0 at this time.

Assume M_m represents the moment generated by the balancing mechanism and the relationship of Eq. 12 can be obtained when the roll angle φ is small:

$$Mm = \rho\Delta gL\cos\varphi = -0.062x^2-1.34x+42.02 \quad (12)$$

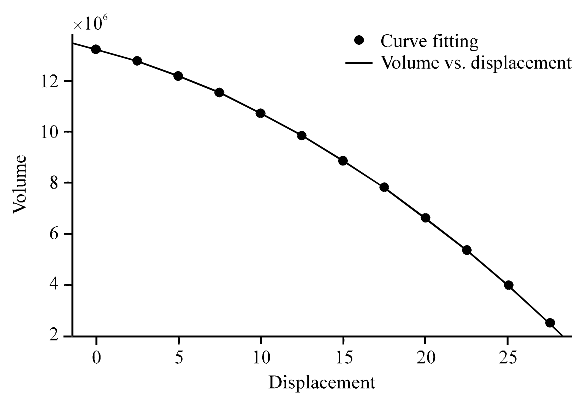

Fig. 6: Volume-time fitting curve of unfolding-closing process of the magic ball

Table 1: Parameter variation in unfolding-closing process of the magic ball

Time t(sec)	Relative position of the movable block 1, 2 (mm)	Displacement of movable block 2 X (mm)	Diameter D (mm)	Volume V (10^6 mm^3)
0.0	48.21	27.48	168.94	2.52
0.2	43.21	22.48	217.27	5.37
0.4	38.21	17.49	246.13	7.81
0.6	33.21	12.49	266.05	9.86
0.8	28.22	7.49	280.16	11.51
1.0	23.22	2.50	289.95	12.76
1.1	20.72	0.00	293.48	13.24

According to the relationship of Eq. 11 and 12, when the movable block 2 is operating in a constant speed, through controlling the displacement of the movable block 2 to achieve the control of the ball volume change. Therefore, it can be realized to generate the desired buoyancy torque in response to different levels of external interference by controlling the displacement of the movable block 2.

SIMULATION ANALSIS OF THE BALANCING MECHANISM FOR UNDERWATER VEHICLE ROLLING MOTION

The underwater vehicle will generate rolling motion regarding the x-axis as the center axis under external interference in y-axis. According to the Conolly theory, the vehicle roll equation is established in the case of small roll angle (Li *et al*., 2003, 2010):

$$(I+\Delta I)\ddot{\varphi}+2N\dot{\varphi}+Dh\varphi+M_m=M(t) \quad (13)$$

I and ΔI in equation (13) represent the underwater vehicle roll quality and attachment quality of the inertia moment of the x-axis. The value of ΔI is generally represented 10-30% of the roll inertia moment and take 20% in this study; 2N is the underwater vehicle roll damping torque scaling factor and it is taken as 0.126 here; D is the discharge of water of the underwater vehicle system; h is the transverse met centric height; M(t) is external interference moment and M_m is righting moment generated by balancing mechanism; φ, $\dot{\varphi}$ and $\ddot{\varphi}$ represent the roll angle, roll angular velocity and roll angular acceleration of the underwater vehicle, respectively.

Take Video Ray PRO II – ROV as the research object and the parameters of this mini underwater vehicle: Length 30 cm, width 23 cm, high 23 cm, quality 4.5 kg. The material of magic ball is aluminum alloy. Table 2 shows the other theoretical parameters of the underwater vehicle.

The transfer function of rolling motion can be obtained through Eq. 13 Laplace transform. Equation 15 and 16 present the transfer function of two cases of underwater vehicle with balancing mechanism and without balancing mechanism:

$$G(s)=\frac{1}{0.0356s^2+0.126s+1.27} \quad (14)$$

$$G(s)=\frac{1}{0.0557s^2+0.126s+2.53} \quad (15)$$

Assume the value of external interference moment is M(t):

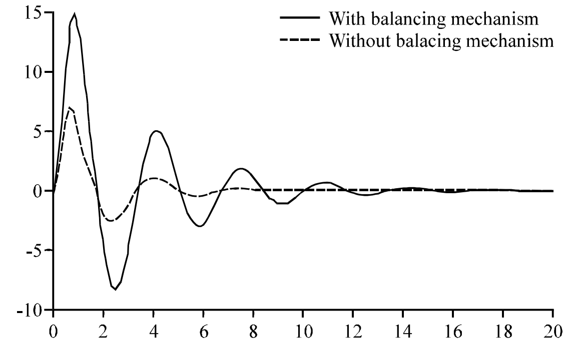

Fig. 7: Relationship diagram of roll angle-time with balancing mechanism and without balancing mechanism

Table 2: Theoretical parameters of roll equation with balancing mechanism and without balancing mechanism

Parameters	I_1 (kg m^2)	D (kg)	h (m)
With balancing mechanism	0.0297	15.87	0.08
Without balancing mechanism	0.0464	31.63	0.08

$$M(t)=20e^{-0.3t}\sin 0.6\pi t \quad (16)$$

According to transfer function 14 and 15, using MATLAB Simulink simulation analysis tool to obtain the changes of the roll angle with time in two cases, as shown in Fig. 7.

As shown in Fig. 7, when the underwater vehicle is affected by external interference, the underwater vehicle' roll angle is up to 14.8° without the balancing mechanism; However, the maximum roll angle is 7.2° when the underwater vehicle is equipped with the balancing mechanism. In both cases, the vehicle balance attitude adjustment time is reduced from 14.3-6.8 sec, basically achieve the balance control.

CONCLUSION

This study proposes a balance control mechanism for mini underwater vehicle. The proposed balance control mechanism is based on position control of gas in four floating balls through the floating balls expansion and shrinkage and then changing the local buoyancy of entire underwater vehicle to generate the righting moment for vehicle balanced attitude adjustment. The expansion and shrinkage of the inflatable floating ball is accomplished by the magic ball's unfolding and closing and the volume of the floating ball in expansion state is 5.25 times bigger than that in shrinkage. Therefore, the movable block movement in short route can achieve a wide range volume change of the floating balls and consequently meet the underwater robot external interference ability to respond quickly and the requirement of the change of the local buoyancy. The feasibility of the balancing mechanism can be initially verified by the proposed balancing mechanism which utilizes the rolling motion simulation analysis.

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