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Modeling and Control of a Bionic Bladder System Designed for Bionic Underwater Robots

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Abstract: Bionic underwater robot is a new-type underwater robot which propelled and controlled by several bionic fins. Heaving motion is an indispensably function for most bionic underwater robots. Bionic bladder system is an apparatus which can realize both heaving and pitching control. It was inspired by biologic fish's bladder. It was composed of a cylinder, a piston, a pipe, a rolling guide, two ball screws and two servomotors. The dynamic models of the bionic bladder system for heaving and pitching motion were established and based on which a dual-velocity control system was designed. Two control channels realized decoupling by setting different control cycles, and a PID controller are designed for each control channel. Simulations with the real design parameters and different control cycles were performed. Results indicated that the bionic bladder system can get a good control performance with proper control parameters.

Keywords: Bionic underwater robot; Bionic bladder system; Heaving and pitching motion; Dual-velocity control system; PID controller.

1. Introduction

Oceans play an important role in human existence. Inherent human curiosity and its fascination for exploring new environments together with the need for new resources compelled people to invent machines and engineer vehicles with which to travel over the seas, and then to dive under them. In this context, underwater robots are becoming a hot topic increasingly all over the world.

Inspired by the prominent capability of fishes to swimming in the water, scientists and engineers of underwater robots have put their great interest in fishes for a long time, but few successes have been achieved till the late of 20th century due to the insufficiency of bionics, robotics, materials and cybernetics. The first robotic fish RoboTuna appeared in Massachusetts Institute of Technology in 1994 [1], which opens the enterprise of making kinds of bionic underwater robots. And for sure, many bionic underwater robots emerged all over the world with different novel characteristics, such as Blackbass, two-joint Dolphin Robot, UPF, SPC, Fish-like Robot with two undulating side fins, NTU robotic fish with modular flexible fins [2-6], and so on. Generally, these bionic underwater robots have a small volume, and can move with preferable maneuverability such as surging, yawing and heaving.

As an important part of the underwater robot, especially the bionic underwater robot, heaving motion system attracts researchers for a long time. Traditionally, it was composed of screw propeller and steering rudder in underwater robots [7]. This kind of system, which can only realize diving and climbing dynamically, exists large coupling in

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vertical and horizontal maneuverability, thus makes a big problem in control system design.

Inspired by the physiological structure of the fish with bladders, researchers have designed many freestanding heaving motion devices [8-11]. Most of them have a big volume and are inclined to cause pitching motion of the robot. The bionic bladder system put forward in this paper behaves more useful. It imitates some fish's physiological structure. Besides the primary function of heaving, the bionic bladder system can also have the function of pitch attitude regulation. It is implemented by movements of both the piston and the base. Among which, the piston is charge of heaving control, while the base is charge of pitch attitude regulation.

This paper is organized as follows. Section 2 introduces the bionic bladder system presented in this paper. In section 3 the dynamic model of the bionic bladder system was built. Section 4 gives the control methods of bionic bladder system, and section 5 is the simulation results of the bionic underwater robot with bionic bladder system.

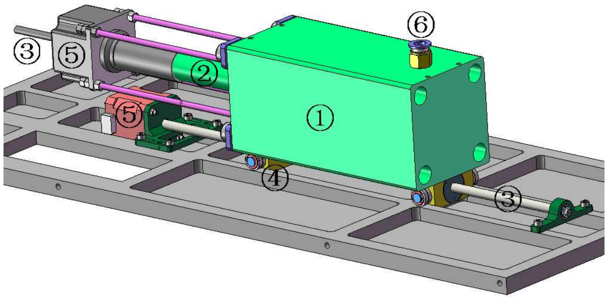
2. Bionic bladder system

When we design underwater robots, neutral buoyancy is required for the most time. But it is hard to implement for some reasons: 1) the accurate of the structure design and processing cannot be guaranteed; 2) underwater robots need to suit various loads sometimes, so the mass of the robot is uncertainty; 3) the volume of the underwater robot is inconstant owing to the hydraulic pressure, consequently the buoyancy is inconstant too; 4) the change of the liquid medium and environment such as temperature and salinity will also cause the change of buoyancy. Therefore, the underwater robot needs to adjust its mass when the mass or buoyancy error appears, thus reach the balance, or neutral buoyancy.

In addition, heaving motion is an indispensably function for underwater robots [12, 13]. Diving into the water and climbing up to the surface are the basic motion for underwater robots, with which the robot can rise quickly when emergency appears. This function also requires the underwater robot to adjust its mass.

The pitch attitude regulation when no surge speed is also an important question need to take into account in underwater robot design. The asymmetry distributing of the mass and the pitch moment brought by diving or climbing will cause the pitching motion of the robot. This means that we must design corresponding pitch attitude regulation system to keep the underwater robot balance in horizontal direction.

To solve the problems presented above, we design a bionic bladder system for minitype underwater robot, as shown in Figure.1. It is composed of a cylinder, a piston, a pipe, two ball screws, a rolling guide and two servomotors. The cylinder is fixed relative to the servomotor driving the piston, and installed in the inner part of the robot via a rolling guide. The cylinder can move along the rolling guide by another servomotor. The piston moves inside the cylinder, consequently change the volume of the cylinder's cavum and adjust the mass of the robot. At the same time, driven by the servomotor, the base which includes the cylinder and piston together moves inside the robot, consequently adjust the pitch attitude of the robot.



①cylinder; ②piston; ③ball screw; ④rolling guide; ⑤servomotor; ⑥pipe

Figure.1 Structure of the bionic bladder system

From Figure.1 we can see that, the bionic bladder system has some distinct advantages. It has a small volume, and the structure is relative straightforward. In addition, it can be encapsulated as a unit and fixed under the robot when needed, which means modularization. The cavum is filled with water via the pipe when the robot is put into water. If the press sensor installed in the robot shows that the robot is not in neutral buoyancy and horizontal state, buoyancy and pitch attitude of the underwater robot can be adjusted simultaneously by the cooperative movement of the piston and the base. From a rough analysis, the movement of the base will not change the buoyancy of the robot, but the movement of the piston has influence upon buoyancy and pitch attitude. Therefore, we should design a cooperative control system for the piston and the base and realize the decoupling control.

3. Dynamic Model

The reference frame of the underwater robot is shown in Figure.2 [14, 15]. The origin is set to the near center of buoyancy of the underwater robot, and close to one side of the cylinder. The X-axis is along with the longitudinal axis and positive when pointing to ahead. The Y-axis is vertical to the X-axis, and positive when pointing down and placed flatly. The Z-axis is vertical to OXY plane, and makes the OXYZ a right-hand reference frame.

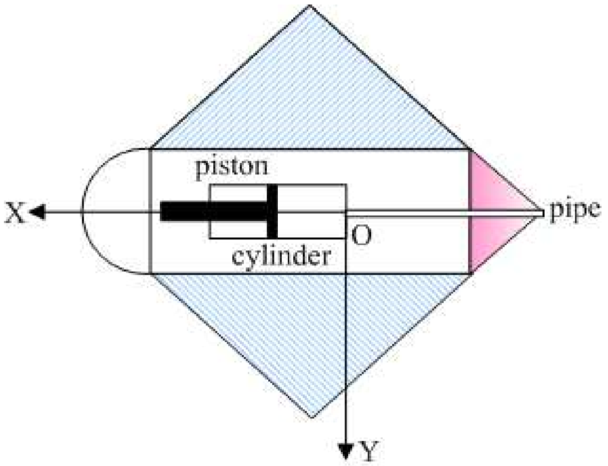


Figure.2 Reference frame of the underwater robot

Let the displacement changes of the piston and the base are Δh and Δx respectively; the mass of the cylinder system except the piston and liquid is m_1, and its initial center of gravity is x_1; the mass of the piston and water are m_2 and $\Delta m = \rho S(x_0 + \Delta h)$ respectively, and their initial centers of gravity are x_2 and $(x_0 + \Delta h)/2 + \Delta x$ respectively, where x_0 is the initial position of the side of the piston which near the water, ρ is the density of the water, and S is the cross section area of the cylinder; the mass of the underwater robot except the bionic bladder system is M, and its initial center of gravity is x_M. So after the move of the piston and the base, the center of gravity of the underwater robot can be written as

$$x_c(\Delta x, \Delta h) = \frac{m_1 + m_2 + \rho S(x_0 + \Delta h)}{m_1 + m_2 + \rho S(x_0 + \Delta h) + M}\Delta x + \frac{x_1 m_1 + x_2 m_2 + \Delta h m_2 + (x_0 + \Delta h)^2 \rho S / 2 + x_M M}{m_1 + m_2 + \rho S(x_0 + \Delta h) + M} \quad (1)$$

From equation (1) we can seen that, the displacement change of the base has an linear influence on the center of gravity of the underwater robot, while the displacement change of the piston has an nonlinear influence. It also indicates that the pitch attitude of the underwater robot will change when we use this bionic bladder system to heaving control by change the displacement of the piston. This is why we introduce the displacement change of the base.

Assuming the robot is in neutral buoyancy state when $\Delta h = 0$ and $x_0 = x_0^*$. Let the mass and buoyancy of the robot are m and f_0 respectively, then $m = m_1 + m_2 + \rho S x_0 + M$ and $f_0 = -mg$.

Let the depth of the underwater robot is y, the dynamic equation of heaving motion with the piston movement is

$$\ddot{y} = \frac{\rho S g \Delta h - \Delta V \rho g - \frac{1}{2}\rho S_{By} C_y \dot{y}^2}{m + \rho S \Delta h + \lambda_{22}} \quad (2)$$

Where λ_{22} is a coefficient of the accessional inertia force, S_{By} is the vertical characteristic area, and C_y is the lift coefficient. If neglect the volume change of the robot ΔV, we have

$$\ddot{y} = \frac{2\rho S g \Delta h - \rho S_{By} C_y}{2(m + \rho S \Delta h + \lambda_{22})}\dot{y}^2 \quad (3)$$

This is the dynamic model of heaving motion of the underwater robot driven by the bionic bladder system.

The movement of the piston and the base will work on the pitch attitude of the underwater robot. As the heaving motion belongs to slow system, we can assume that the robot has no vertical movement when deduce the dynamic equation of pitching motion. Therefore, the dynamic equation of pitching motion can be expressed as

$$(J_z + \lambda_{66})\ddot{\theta} = M_z = -x_c(\Delta x, \Delta h) \cdot f \quad (4)$$

Where θ is the pitch angle, J_z is the moment of inertia of Z-axis, and λ_{66} is a coefficient of the accessional inertia force. Neglecting the volume change of the underwater robot, the buoyancy f should be a constant, i.e. $f = f_0 = -mg$. So we have

$$\ddot{\theta} = \frac{-x_c(\Delta x, \Delta h) \cdot f}{J_z + \lambda_{66}} = \frac{x_c(\Delta x, \Delta h) mg}{J_z + \lambda_{66}} \quad (5)$$

This is the dynamic model of pitching motion of the underwater robot driven by the bionic bladder system.

4. Control Methods

From above analysis, we can see that the bionic bladder system is a MIMO system whose input parameters are displacements of the piston and the base, and output parameters are pitch angle and depth [16-18]. In addition, it is a nonaffine nonlinear system with input saturation. In the most time, the desire pitch angle of the underwater robot is a constant, i.e. zero.

According to (3) and (5), the heaving control channel is only related to the displacement of the piston while the pitching control channel is related to displacements of both the piston and the base. The nature idea is to decouple the pitching control channel and heaving control channel by controller design. Here, we put forward a dual-velocity control system where the heaving channel adopts slow velocity while the pitching channel adopts fast velocity [14]. Consequently, the position of the piston can be regarded as a constant in pitching control cycle. So the pitching control channel becomes a SISO system, and the bionic bladder system realizes decoupling control.

Similar PID controllers are adopted in the heaving channel and pitching channel. If the control error of the controller in cycle k is $e(k)$, the control input is $\Delta u(k)$, then

$$\begin{aligned}\Delta u(k) = K_p[e(k) - e(k-1)] + K_i e(k) \\ + k_d[e(k) - 2e(k-1) + e(k-2)]\end{aligned} \tag{6}$$

Where K_p, K_i and K_d are the proportional coefficient, integral coefficient and differential coefficient respectively. To the heaving channel, the control input $\Delta u(k)$ is the displacement of the piston. To the pitching channel, $\Delta u(k)$ is the displacement of the base as the piston can be seen as fixed in pitching control cycle.

The three PID parameters can be fixed primarily by experience, then make adjustment through simulation experiments. However, we can't get the accurate plant model on most occasions, and even though we get, the bionic bladder system will face many disturbances and uncertainties. It means that the PID parameters must be changed online. Here, a simple fuzzy logic system is adopted. Several adjust rules are fixed about each PID parameter according to the practical operation experiences.

5. Simulation

To verify the control performance of the bionic bladder system, we design a prototype for the bionic underwater robot with bionic bladder system. The design parameters are concluded in Table 1. According to these parameters, the maximum gravity provided by the bionic bladder is about 5N. Since the piston is usually in the middle of the cylinder when the bionic underwater robot is in neutral buoyancy state, the maximum net buoyancy provided by this bionic bladder system is about 2.5N.

Table 1. Design parameters of the bionic bladder based underwater robot

Parameter	Value	Parameter	Value
m_1	4.2 kg	x_1	0
m_2	0.3 kg	x_2	0
M	55.5 kg	x_M	0
f_0	590 N	x_0^*	0.03 m
D	0.1 m	S_{By}	0.432 m^2
L	0.065 m	C_y	0.46
λ_{22}	50.4 kg.m^2	λ_{66}	3.96 kg.m^2
J_Z	7.85 kg.m^2		

According to the data in Table 1, we can get the open loop response characteristic of the underwater robot when it diving with full speed, as shown in Figure.3, which includes the change of depth, velocity and acceleration. The maximum velocity is about 0.165m/s, and it needs 11s to dive to 1m underwater.

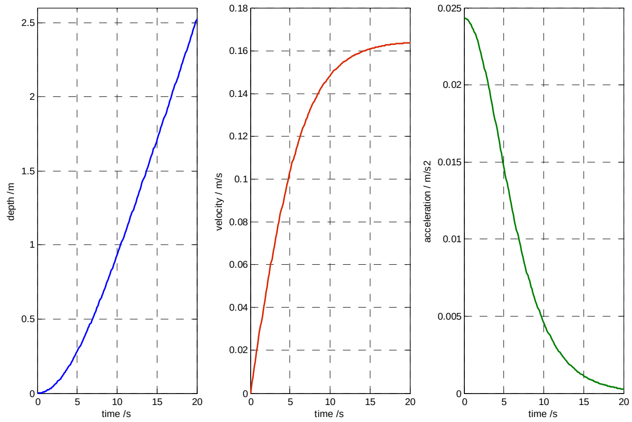


Figure.3 Open loop response characteristic of the bionic underwater robot with bionic bladder system

The Matlab/Simulink simulation model of the bionic bladder system is shown in Figure.4. The heaving control channel and pitching control channel are full independent at any time. The pitch model is a time variant model since its parameters are functions of piston's placement in heaving control cycle. The two control channels both adopt PID controllers, and their initial PID parameters are optimized by Simulink Response Optimization toolbox. The fuzzy logic system will adjust these PID parameters online. The optimized initial parameters are listed in Table 2.

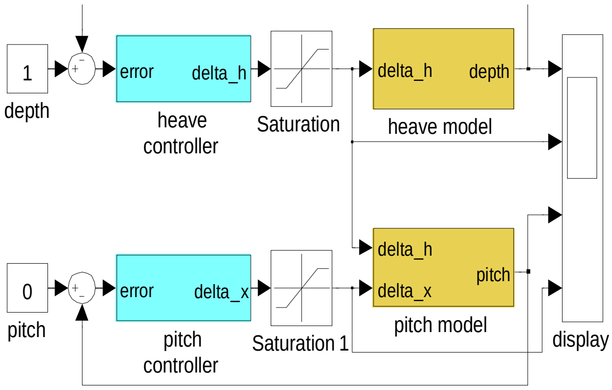


Figure.4 Block diagram of the control system for bionic bladder system

Table 2. Initial parameters of the control system

Parameter	Heaving Control	Pitching Control
K_p	20	60
K_i	0.01	0.05
K_d	30	30

Usually, the selection of control cycle is important to dual-velocity control system. Here, we give simulations to different combinations of control channel and control cycle to check their control performance. The simulation parameters are as follows: the desired depth is 1m; fix step simulation; step is 0.01s, and solver is ode3; simulation time is 40s. The simulation results are shown from Figure.5 to Figure.8.

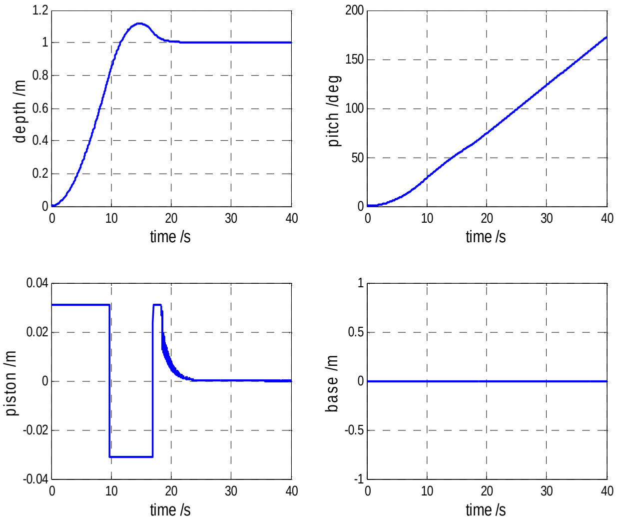


Figure.5 Performance of the bionic underwater robot with heaving control only (Heaving control cycle is 0.1s)

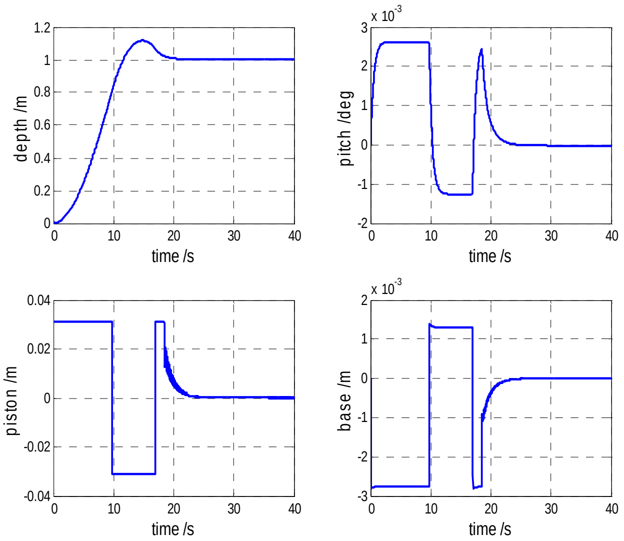


Figure.6 Performance of the bionic underwater robot with both heaving and pitching control (Control cycles of the heaving channel and pitching control are 0.1s and 0.01s respectively)

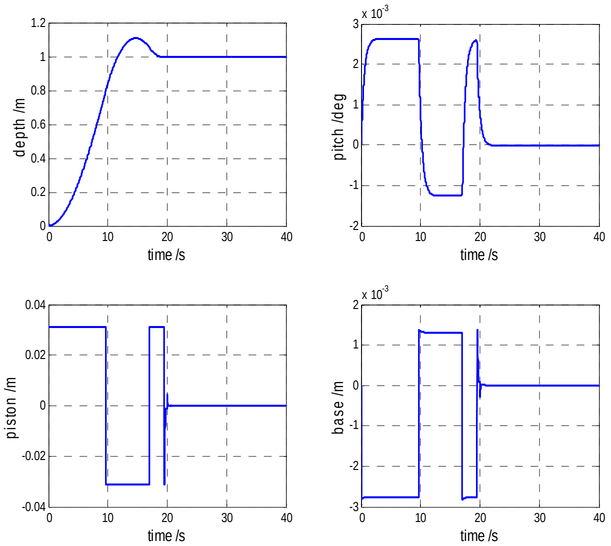


Figure.7 Performance of the bionic underwater robot with both heaving and pitching control (Control cycles of the heaving channel and pitching control are 0.5s and 0.01s respectively)

According to above results, the bionic underwater robot needs about 20s to dive to 1m depth steadily. If exerting heaving control alone, the robot’s stability cannot be guaranteed. The values of the heaving control cycle and pitching control cycle have a small influence to the control performance. The overshoot is near to 11%, and the steady accuracy is perfect. It is seen that, proper control parameters selected, good control performance can be achieved with the conventional PID controller.

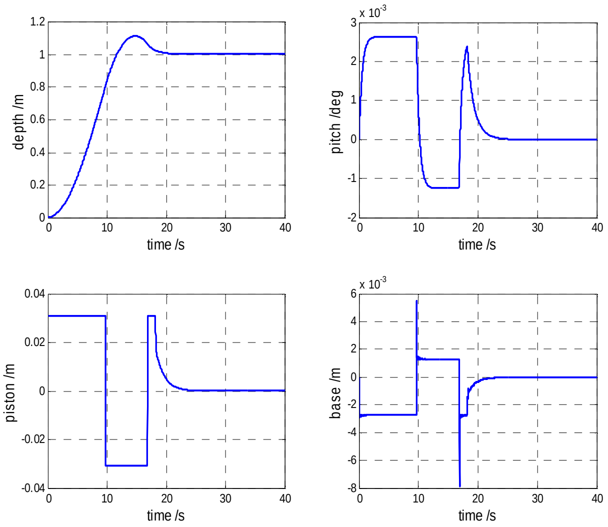


Figure.8 Performance of the bionic underwater robot with both heaving and pitching control (Control cycles of the heaving channel and pitching control are 0.01s and 0.1s respectively)

6. Conclusions

The small volume, simple structure, modularity, together with favorable control performance make the bionic bladder system has extensive applications in minitype bionic underwater robots. This paper gave a general introduction to the bionic bladder system, deduced its dynamic models for heaving and pitching motion, and designed a dual-velocity control system which realized decoupling between heaving motion and pitching motion. Simulations with the real design parameters were carried out. Results indicated that the satisfying control performance can be achieved by two conventional PID controllers and the bionic bladder system is applicable in the bionic underwater robot.

Acknowledgments

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