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Control algorithm of underwater robot's attitude based on PID control[1]

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Abstract. The stability of the underwater robot's pose plays a decisive role in the accuracy of underwater robot's work. In order to improve the stability of robot's pose, the underwater robot is designed for the full symmetrical mechanical structure. Then we establish the dynamic model, complete the design of the control algorithm and verify the effectiveness of the designed algorithm by MATLAB/Simulink and navigation experiment. The results of simulation show that: The algorithm can effectively complete the stability of the underwater robot navigation attitude control. Underwater navigation experiments showed: The control algorithm based on the symmetry of the structure can effectively correct the navigation attitude deviation which is caused by the undersea complex flow disturbance. The results have a certain reference value and practical significance for the stability of the underwater robot attitude control.

Key words. Underwater robot, control algorithm, attitude control, dynamics analysis..

1. Introduction

In recent years, the research of underwater robot has gradually become the new frontier and hot issue in the study of navigation. As the prospecting in ocean floor and the development of submarine cable maintenance, the application prospects of underwater robot in deep become more extensive. At the same time, the require-

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ment of underwater robot mobility and maneuverability become higher and higher. In the process of underwater robot to complete a task, it requires not only the robot can be in accordance with a predetermined trajectory, but also the using of underwater robot to the target for more detailed observation and operation. This would require the robot relative to the target position remains unchanged, which mains the underwater robot has to withstand high postural stability of the disturbance of environment. The robot can ups and downs vertically at the bottom of the ocean and we can complete the control system for the robot navigation through all four symmetrical distribution of propeller speed adjustment. The robot's structure is more compact, because of not using stern rudder. The propulsion of four propellers is more uniform than more propellers. It is easier to adjust the attitude. So the navigation attitude is more stable. The robot can realize fixed depth sailing, the spin of zero point and the accuracy of the attitude control is high.

Accurate control of underwater robot technology is a key technology in robot control. Harbin engineering university has done the detailed research on the underwater robot modeling method. Shenyang research institute of automation develop major no LAN underwater robot. Shanghai Jiao Tong University has proposed new underwater robot control method base on neural network and designed the underwater robot. MIT has developed the underwater robot controller base on fuzzy control algorithm and do some actual application. The current research is focus on the field of nonlinear control, because the nonlinear control has strong dependence on the accuracy of the model. When the model still has some error, PID control is a kind of more practical method. The article introduces the design of the PID controller which base on the four propeller symmetric distribution equilibrium structure.

2. Overall design of the robot

The robot uses AV camera to take images, and display on the screen. Due to the data which AV camera collects cannot be handled on OPENCV, we use the general web camera for the image processing. The image collected by camera processed on a computer through OPENCV.

The robot's main control chip is Arduino Mega2560. Direction sensor MPU-6050 collects data and sends the data to the upper machine to display.

Handheld terminals use handheld terminal operating mode. The two sides communicate with each other by USB Host Shield V2.0 and Mage2560. Control signal is passed to the robot through the RS485 to achieve the control of the robot.

The overall design is shown in Fig. 1. The design of robot appearance is shown in Fig. 2.

3. The mechanical structure design

What is the most difficult for underwater robot to be able to complete the intricate movements under water is its attitude control under the complex environment of underwater. To meet the basic requirement of the robot posture algorithm, de-

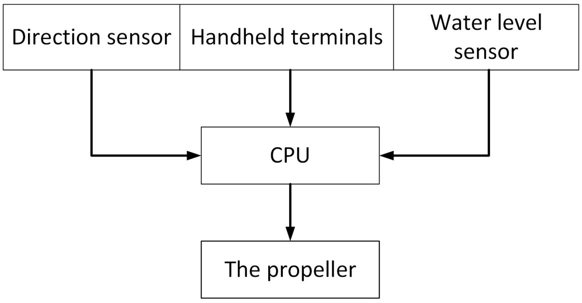

Fig. 1. The overall block diagram

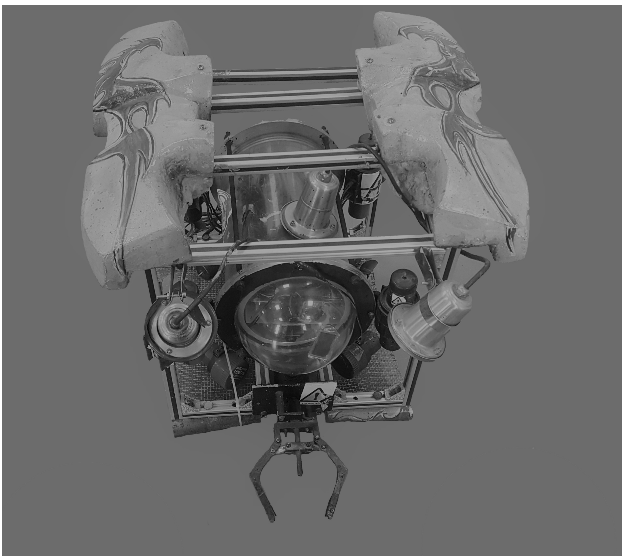

Fig. 2. Robot rendering

signing good mechanical structure is the basic guarantee for the attitude algorithm. So the designing of self balancing system which is base on the mechanical structure is an important aspect.

In order to meet the design of robot's balance, balance structure design and algorithm design become the two aspects of complement each other. The main characteristic of a self balancing system control system which is the most difficult to solve is that we use the angle of the system in the vertical direction or horizontal displacement of as control object and control it in a certain range. A system that the center of gravity in the above and protection in the follow is a self balancing control system. We need to design an open box framework. We choose aluminum because of its small density, good durability and low cost. In the process of design, we need to consider the following several aspects. The first is the matching of flotation and gravity. Steel plate is in the following and buoy is in the above. This makes the robot's center of gravity is low and easy to stable. The second is that in the process of the underwater robot to complete the task, center of gravity changes. The robot tries to ensure stability. Thrusters are symmetrically arranged and the center of gravity is as far as possible in the middle of the robot. This layout is easy to ensure stability.

4. The design of attitude control algorithm

The software design process of the Robot attitude control system is shown in Fig. 3. The system first initialized to the sensor, direction sensor measures attitude Angle and angular velocity of the robot, depth sensor is to measure the depth of the robot. After the parameter acquisition, using PID algorithm to adjust the attitude angle of robot, calculate the speed of the propeller, send speed to the propeller [1].

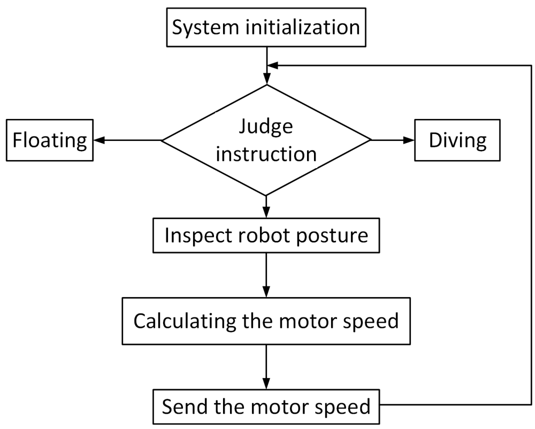

Fig. 3. The software design process of the Robot attitude control system

Four rotor aircraft hovering and accurate location provides us with a train of thought to solve the difficulties of the underwater robot. Through the analysis about the structure of airborne robots, we find that it is easy for airborne robots to realize vertical lifting and precise attitude adjustment because of its completely symmetrical structure. We get the symmetrical structure of the underwater robot on the basis of the analysis of the air robot's mechanism. The layout of the four propellers is the balance layout structure. As shown in Fig. 4, in order to obtain the dynamic model of underwater robot, we had a mechanical analysis of underwater robot and establish two coordinate on the basis of the analysis: inertial coordinate system $E(OXYZ)$ and the robot coordinate system $B(OXYZ)$, defining Euler angle, respectively, as the following [2]:

- Yaw Angle ψ: ox in oxy plane projection and x axis angle.
- Pitching Angle θ: oz in oxz plane projection and z axis angle.

- Rolling Angle Φ: oy in oyz plane projection and x axis angle, as shown in Fig. 3.

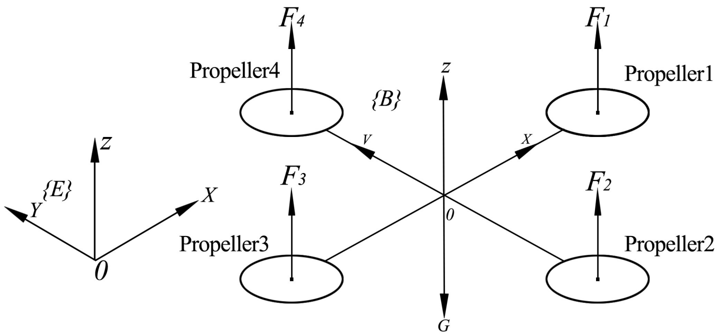

Fig. 4. The establishment of the mathematical model

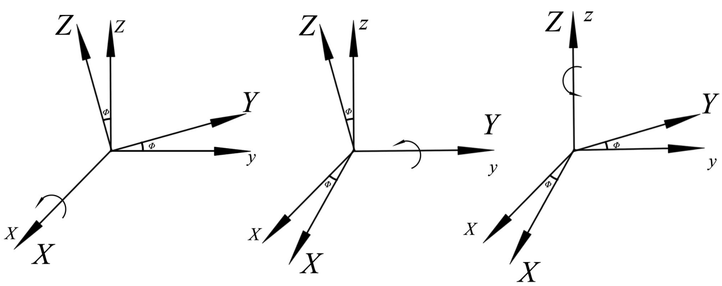

Fig. 5. Euler angle

Transformation matrix of the robot coordinate system to the inertial coordinate system

$$R = R_{\mathrm{x}} \cdot R_{\mathrm{y}} \cdot R_{\mathrm{z}} = \begin{pmatrix} \cos\psi\cos\phi & \cos\psi\sin\theta\sin\phi & \cos\psi\sin\theta\cos\phi + \sin\psi sn\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi & \sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{pmatrix}. \tag{1}$$

In order to establish a dynamic model of underwater robot and do not break general, we make the following assumptions:

1. Robot's body is homogeneous symmetric distribution [3].
2. The origin of the inertial coordinate system E is located in the same location with a robot geometry center and center of mass.
3. An underwater robot suffered resistance and gravity is not affected by factors such as depth of underwater navigation. After weight, it makes the whole machine's density little heavy and always remains the same.

4. Tensile strength of the robot in all directions is direct ratio to the square of the propeller rotation speed.

Definition of F_x, F_y, F_z for $\boldsymbol{F}$ in the robot coordinate system on the three axes component; Definition of P, q, r for the angular velocity omega three axes in the robot coordinate system.

Newton's second law and robot dynamics equation can be expressed respectively in the vector form

$$\boldsymbol{F} = m\frac{\mathrm{d}V}{\mathrm{d}t}\,, M = \frac{\mathrm{d}H}{\mathrm{d}t}\,. \tag{2}$$

In the formula, $\boldsymbol{F}$ is the external force on the underwater robot, m is the quality of the robot, V is the speed of the robot, M is the sum of the torques by robots, H is absolute moment of momentum of the robot relative to the ground coordinate system, G is the gravity, D_i is resistance, a single rotor lift T_i said as follows [4]

$$G = mg\,,\ D_\mathrm{i} = \rho C_\mathrm{d}\omega_\mathrm{i}^2/2 = k_\mathrm{d}\omega_\mathrm{i}^2\,,\ T_\mathrm{i} = \rho C_\mathrm{t}\omega_\mathrm{i}^2/2 = k_\mathrm{t}\omega_\mathrm{i}^2\,. \tag{3}$$

According to stress analysis, we can obtain line equation of motion by Newton's second law and the robot dynamics equation. As shown in the following [5]

$$\begin{aligned} \ddot{x} &= (F_x - K_1\dot{x})/m = (k_\mathrm{t}\textstyle\sum_{i=1}^4 \omega_i^2(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi) - K_1\dot{x})/m\,, \\ \ddot{y} &= (F_y - K_2\dot{y})/m = (k_\mathrm{t}\textstyle\sum_{i=1}^4 \omega_i^2(\sin\psi\sin\phi\cos\phi - \cos\psi\sin\phi) - K_2\dot{y})/m\,, \\ \ddot{z} &= (F_z - K_3\dot{z})/m = (k_\mathrm{t}\textstyle\sum_{i=1}^4 \omega_i^2(\cos\phi\cos\phi) - K_3\dot{z})/m - g\,. \end{aligned} \tag{4}$$

We can get the following matrix based on Euler angle and angular velocity of the relationship between robots

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} p\cos\theta + q\sin\phi\sin\theta + r\cos\phi\sin\theta)/\cos\theta \\ q\cos\phi + r\sin\phi \\ (q\sin\phi + r\cos)/\cos\theta \end{bmatrix}. \tag{5}$$

We have been assuming that the quality of the underwater robot and structure are uniform symmetric. So, its inertia matrix can be defined as diagonal matrix $\boldsymbol{I}$ by the calculation of moment of momentum. We can get angular motion equations of M in the robot coordinate system three axial component M_x, M_y, M_z.

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} [M_x + (I_x - I_z)qr]/I_x \\ [M_y + (I_z - I_x)rp]/I_y \\ [M_z + (I_x - I_y)pq]/I_z \end{bmatrix}. \tag{6}$$

Defining the U_1, U_2, U_3, U_4 for underwater robot four independent control channel's control input

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} F_1 + F_2 + F_3 + F_4 \\ F_4 - F_2 \\ F_3 - F_1 \\ F_2 + F_4 - F_3 - F_1 \end{bmatrix} = \begin{bmatrix} k_\mathrm{t}\sum_{i=1}^4 \omega_i^2 \\ k_\mathrm{t}(\omega_4^2 - \omega_2^2) \\ k_\mathrm{t}(\omega_3^2 - \omega_1^2) \\ k_\mathrm{d}(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \end{bmatrix}. \tag{7}$$

In the formula, U_1 is vertical speed control input, U_2 is rolling control input, U_3 is pitch control input, U_4 is yaw control input. ω is the speed of the propeller, F_{i} is the pulling force that propeller suffers. Through the line equation of motion and angular motion equation, we can get the nonlinear equations of motion of the robot. Among them, I is the distance from the propeller center to coordinate system origin, K_{i} is the damping coefficient of the water. Under the condition of the water is static or flow slowly, we can study and overlook the damping coefficient of water. The finishing mathematical model is as follows [6]

$$\begin{array}{ll} \ddot{x} = (\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi)U_1/m\,, & \ddot{\phi} = \left[\iota U_2 + \dot{\theta}\dot{\psi}(I_y - I_z)\right]/I_x\,, \\ \ddot{y} = (\sin\psi\sin\phi\cos\phi - \cos\psi\sin\phi)U_1/m\,, & \ddot{\theta} = \left[\iota U_3 + \dot{\phi}\dot{\psi}(I_z - I_x)\right]/I_y\,, \\ \ddot{z} = (\cos\phi\cos\theta)U_1/m - g\,, & \ddot{\psi} = \left[U_4 + \dot{\phi}\dot{\theta}(I_x - I_y)\right]/I_z\,. \end{array} \tag{8}$$

Through the mathematical model of the robot, we can see that the system is a nonlinear, strong coupling, multivariable system. We can break it down and use PID control.

The article has introduced the four control parameters of U and the complex nonlinear coupling model has been decomposed into four independent control channel. So, the model can be seen as the structure of the line movement and angular motion. Through the above modeling, line motion doesn't affect angular motion. However, angular motion affects line motion. We use small disturbance method processing on the basis. After ignoring additional small disturbance, we can get the motion equation of underwater vehicle [7]

$$\begin{aligned} &m\dot{x} = Ax + Bu\,, \\ &x = [\dot{x}, \dot{y}, \dot{z}, p, q, r, \theta, \phi, \psi]^{\mathrm{T}}\,, \\ &u = [u_1, u_2, u_3, u_4]^{\mathrm{T}}\,. \end{aligned} \tag{9}$$

Due to attitude angle and angular velocity this is a quasi integral relation. In order to simplify control system, we assume that the attitude angle and angular velocity have simple integral relationship

$$\dot{\phi} = p,\ \dot{\theta} = q,\ \dot{\psi} = r\,. \tag{10}$$

By the analysis, the open-loop transfer function for the system is shown as follow

$$G(s) = \frac{1}{ms^2}\,. \tag{11}$$

System is not stable because the pole of the open loop transfer function is all at the origin. We increase the differential link to improve the stability of the system. The improved system model is shown in Fig. 6, the improved root locus is shown in Fig. 7.

By the system of root locus, closed loop poles of system are in the top left of the complex plane. System is stable. Closed-loop transfer function of the system is

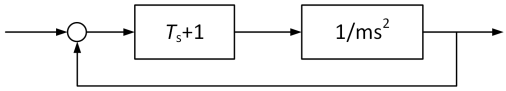

Fig. 6. The improved system model

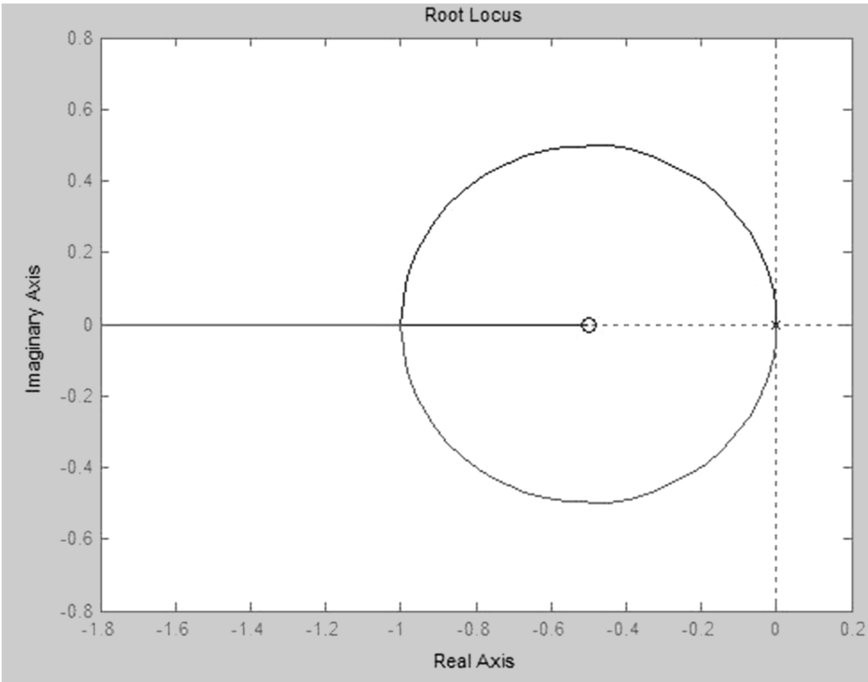

Fig. 7. Improved the root locus of system

shown in the following

$$\Phi\left(s\right)=\frac{2\sqrt{m}s+1}{ms^2+2\sqrt{m}s+1}\,. \tag{12}$$

The roll channel, pitching channel and yawing channel analysis method are similar with this channel.

5. System debugging

Debugging process is divided into two parts: Subsystem debugging alone and the overall debugging.

5.1. *The test of mechanical structure*

After completing the robot's mechanical structure, we install the circuit board and weight the propeller. This makes the robot's density is approximately equal to 1. Then, watch the condition of robot's balance in the water and start the propeller, Observe robot's posture in the water. If the robot's buoyancy is not enough, we can increase the buoy or adding volume floater.

5.2. *The test of sensor system*

First of all, test each sensor alone and ensure that each sensor is in the normal operation. Add program to master control chip, watch parameters are correct or not through serial debugging assistant.

Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads. Watch parameters and the robot's posture by PC. PC is shown in Fig. 8. Finally, add attitude self balancing algorithm to program to see whether it has improved the robot's posture.

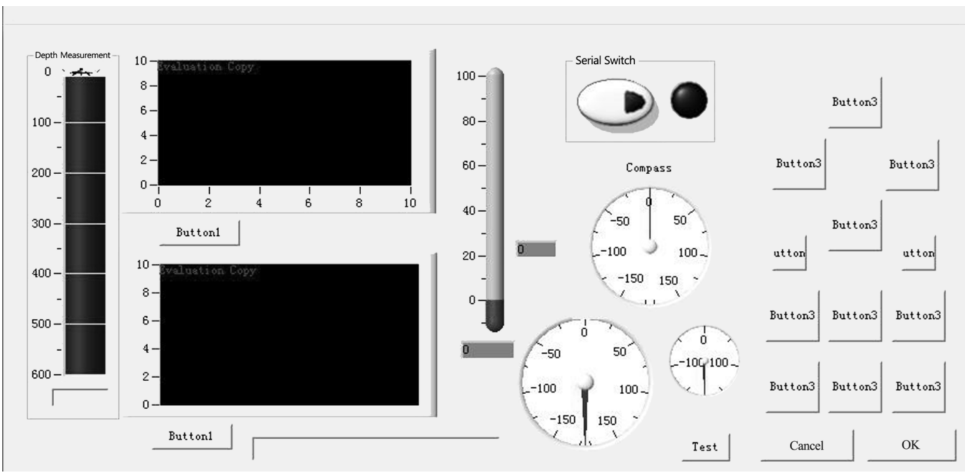

Fig. 8. Upper machine of underwater robot.

5.3. *Control system debugging*

To debug the remote control first, let the Arduino Mega2560 identify handset by USB Host Shield V2.0. Watch the handset to identify whether it is right via a serial port assistant. Then Debug the communication of the two control chips. Let the host to send and slave to receive. Watch the data is correct or not via a serial port debugging assistant. Finally the two parts are debugged together.

Table 1. The underwater robot's parameters.

parameter	value
m (kg)	35.1
L_a (m)	0.424
L_b (m)	0.424
L_c (m)	0.424
I_a (kg $\cdot$ m^2	1.05
I_b (kg $\cdot$ m^2	1.05
I_c (kg $\cdot$ m^2	2.1

Table 2. The transfer function.

Rise channel	$(11.8s + 1)/(35s^2 + 11.8s + 1)$
Roll channel	$(3.15s + 1)/(2.48s^2 + 3.15s + 1)$
Pitch channel	$(3.15s + 1)/(2.48s^2 + 3.15s + 1)$
Yaw channel	$(4.45s + 1)/(4.95s^2 + 4.45s + 1)$

5.4. Video system debugging

Start the AV video camera and connect to the monitor. When debugging USB camera, write a video collection procedures on OPENCV, and run to open. Then combine with image processing and debug.

5.5. Attitude algorithm debugging

According to the underwater robot structural design and reference to the relevant literature, we summarized its parameters in Table 1, and transfer function in Table 2 and Figs. 9–12.

According to the PID system structure, we built a model and performed simulations. After debugging, we found that the overshoot is small, steady-state error is almost zero, and response speed is fast. Simulation verified the effectiveness of the PID control system [8].

6. Conclusion

Using of existing conditions, the underwater robot has goal function by testing various subsystems.

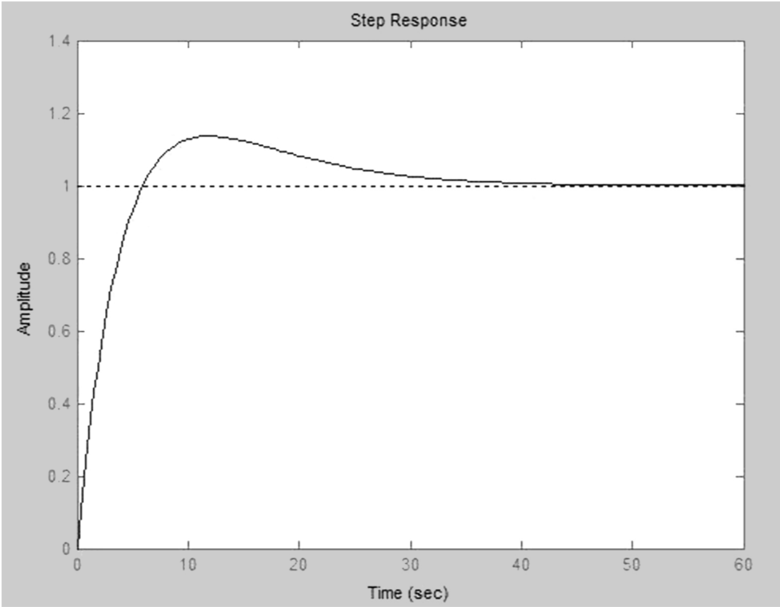

Fig. 9. The transfer function–rise channel

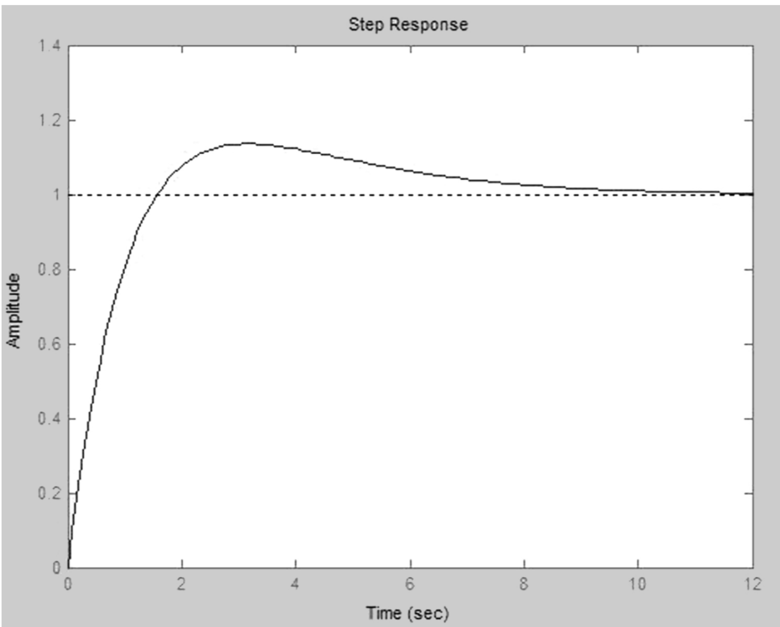

Fig. 10. The transfer function–roll channel

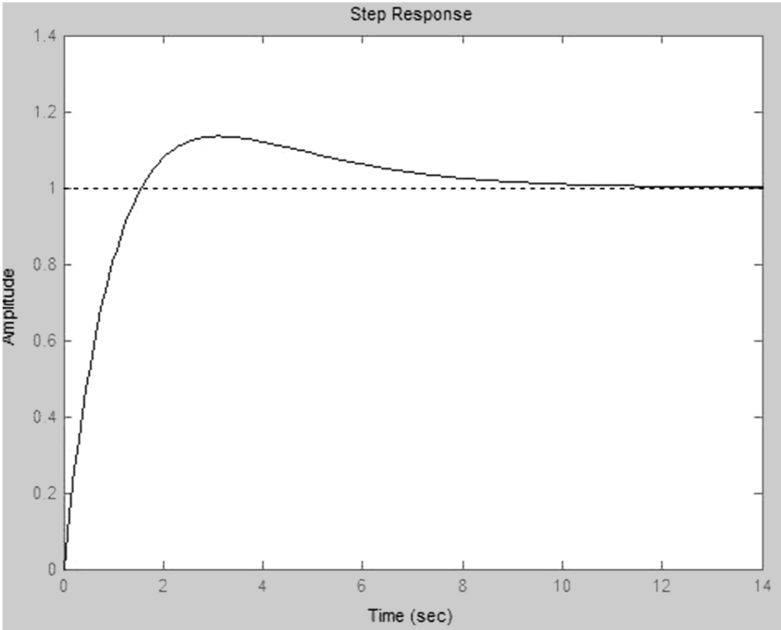

Fig. 11. The transfer function–pitch channel

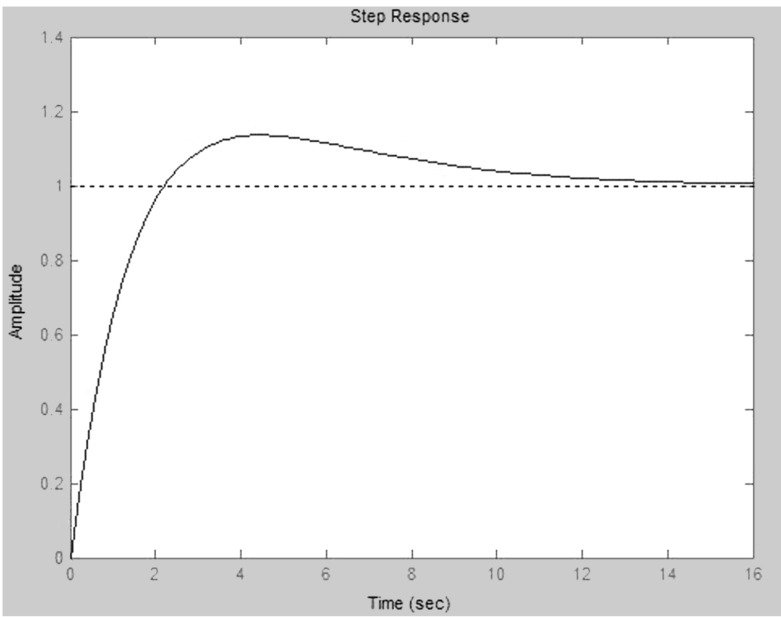

Fig. 12. The transfer function–yaw channel

The robot is divided into mechanical structure, sensor system, control system, video system. Finally, put them together. It meets the requirement of the industrial modularization. We can find problems facilitate and the design thinking is clear. The robot achieves a balanced posture, video monitoring, image processing, measuring the parameters of itself, manipulator operation and a series of functions.

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