DESIGN OF ELECTRONIC DRIVE CONTROL SYSTEM OF THE HYDRAULIC JOINTS OF THE MANIPULATOR

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Abstract - To further improve the control system of the manipulator, the manipulator of the jumbo is taken as the research object. According to the working process of the jumbo and the structure of the manipulator, the electronic drive control system of the hydraulic joints of the jumbo manipulator is designed. Firstly, the overall scheme of the electronic drive control system of the hydraulic joints of the jumbo manipulator is designed, which includes three parts: information collection, information processing, and actuators. Secondly, through the selection of fuzzy subsets and membership functions, the determination of variable domains, quantization factors and proportional factors, and the establishment of fuzzy control rules, fuzzy Proportion Integration Differentiation (PID) controller is designed, and the overall design and software and hardware system of the electronic drive control system of the hydraulic joints of the jumbo manipulator are studied. Finally, the fuzzy controller is designed and simulated through Matrix Laboratory (MATLAB) software. The results show that the rising time of the fuzzy PID controller is about 0.3 seconds, while the rising time of the conventional PID control is about 1 second. Compared with the conventional PID control, the overshoot of the fuzzy PID controller is smaller and can be fast and stable. When disturbed by the 10,000N external load, the fuzzy PID controller responds faster. The maximum peak range is about 1.13, the adjustment time is about 3 seconds. However, the maximum peak range of the conventional PID controller is about 1. 15. The adjustment time is about 3.8 seconds, indicating that compared with the conventional PID controller, the fuzzy PID controller has good dynamic performance, stability, fast response speed, strong tamper-resistance ability and better control effect. The results are conducive to improving the working efficiency of the jumbo manipulator, and providing certain research experience for the research of automatic jumbo.

Keywords: The Jumbo Manipulator, Electronic Drive Control Systems of Hydraulic Joints, Fuzzy PID Controller, System Simulation.

1. Introduction

The jumbo [1] is a piece of engineering equipment used in underground and tunnel engineering construction. It mainly completes the work of drilling blastholes by controlling the joints of the manipulator. The jumbo replaces the work of manual drilling blastholes, reduces the labor intensity and construction cost of underground tunnel construction, and improves the working environment. From the 1960s to the 1970s, foreign countries began to develop hydraulic drills, and companies in the United States, Sweden, Finland, France, Germany, and Japan have invested in them to develop them [2]. In 1980, the first drill in China was successfully developed by Changsha Research Institute of Mining and Metallurgy, Zhuzhou Dongfang Tools Factory and other units. It is the beginning of China's development of hydraulic drills and its supporting drilling equipment.

In recent years, the manipulator control system has achieved fruitful research results. Dobriborsci et al. (2018) [3] studied the design of a robust trajectory tracking controller for parallel robots for non-coiled material handling and dynamic simulation in industrial and medical applications. The controller design was based on an output control algorithm structure and was called the parameter uncertain system of the continuous compensator. Liu et al. (2018) [4] established the mathematical model of the manipulator using the Denavit-Hartenberg parameter method, and designed an inverse solution algorithm based on Newton iteration method. On this basis, the path planning algorithms of cubic interpolation and quintic interpolation in joint space were designed.

Then, the hardware framework and the software system of the manipulator control system were designed, and simulation experiments are carried out. Li et al. (2018) [5] built a multi-body dynamic model of the seven-degree of freedom of mechanism-liquid system according to the characteristics of multi-input and multi-output, nonlinear, rigid and flexible coupling. Meanwhile, a position/force homocyclic control algorithm based on genetic neural network was proposed. The force control system was decomposed into a subsystem, and the feedback of output position and force was processed through the joint position controller, torque controller and multi-body dynamic model. Worapongpat et al. (2020) [6] proposed an improved tracking control method of discrete sliding mode for flexible manipulators. A method of selecting control functions was proposed to ensure the existence of sliding modes and the stability of nominal systems without system uncertainty and interference.

A lot of results have been achieved in the research on the control system of the manipulator, but there are few related types of research on the control system of the manipulator of the jumbo. Based on the study of the working process and the structure of the manipulator, the electronic drive control system of the hydraulic joints of the jumbo manipulator is designed. Firstly, a fuzzy PID controller is designed, and secondly, the overall design and research of the hardware system and software system of the control system are carried out respectively. The fuzzy PID controller is innovatively designed and applied to the electronic drive control system of the manipulator, which further improves the stability of the control system. The research results provide certain research experience for improving the stable operation of the control system of the jumbo manipulator.

2. Design of Electronic Drive Control System of the Hydraulic Joints of the Jumbo Manipulator

2.1 The working process of the jumbo and the structure of the manipulator

The jumbo is a kind of rock drilling equipment used for tunnels and underground engineering construction by drilling and blasting method [7]. It mainly consists of manipulators, propulsion beams and rock drilling rigs. In actual construction, it is first necessary to use relevant software to design the position of the blasthole according to the preset blasting plan and construction requirements, and use the laser equipment to locate the jumbo. Then, the onboard computer of the jumbo is used to control the manipulator according to the designed position of the blasthole, so that the manipulator can locate the blasthole and carry out the work of drilling the blasthole.

In practice, the construction personnel adjust and modify the blasthole according to the working conditions of the jumbo manipulator on site. During the whole work process, the joints of the manipulator are precisely controlled to make it accurate and stable, which is the key factor to improving the construction quality and efficiency of the jumbo. The main work process of the jumbo is shown in Figure 1.

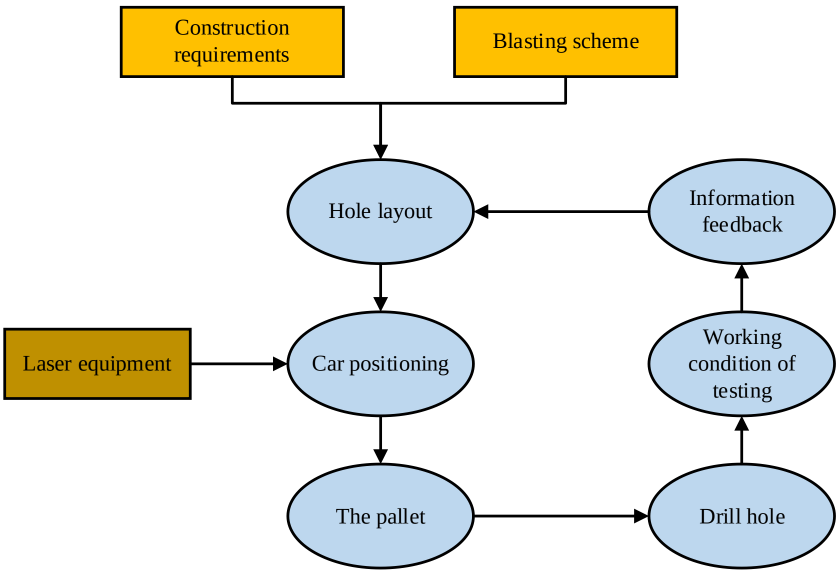


Figure 1: The main work process of the jumbo

The jumbo belongs to large-scale tunnel construction equipment. In actual work, after the body positioning of the jumbo, it will no longer move. The manipulator of the jumbo is controlled by the onboard computer to complete the drilling blasthole. The manipulator of the jumbo is mainly composed of the rear arm, the middle arm, the forearm, the propulsion beam, the drill rod, the rock drilling rig, etc.

Among them, the rear arm part of the jumbo includes the hydraulic cylinder of the left arm and the hydraulic cylinder of the right arm. Its function is to adjust the left and right swing and up and down pitch of the manipulator. There are extension cylinders, left pitch hydraulic cylinders and right pitch hydraulic cylinders in the middle arm. The extension cylinder is mainly used for telescopic movement, and the left pitch Hydraulic cylinders and right pitch hydraulic cylinders adjust the movement of the forearm. The forearm is equipped with a tilting hydraulic motor, a swinging hydraulic cylinder and a compensation hydraulic cylinder. The function of the hydraulic motor is to adjust the angle of the rock driller and the drill rod. The swinging hydraulic cylinder can meet the requirements of the manipulator drill blasthole at different angles, and the compensation hydraulic cylinder can meet the needs of different roughness of the construction section to compensate the propulsion beam for a certain distance and lock the propulsion beam in the actual construction.

Therefore, in the actual work, the main functions to be completed by the manipulator are: telescopic function of the forearm, left and right swing and up and down pitching functions of the forearm, the overturning function of the propeller, the compensation function of the propeller and the normal rock drilling function.

2.2 The Overall Design of the Control System of the Manipulator

The hydraulic control system of the manipulator is mainly composed of three parts: information collection, information processing and actuator. In the part of the information collection, the temperature, position, pressure and other information are obtained through sensors, and then the collected information is transmitted to the part of the information processing. Usually, PLC (Programmable Logic Controller) [8] is used in this part, and the PLC transmits the processed data to the actuator, and controls the action of the manipulator through the hydraulic system [9]. Its overall design scheme is shown in Figure 2.

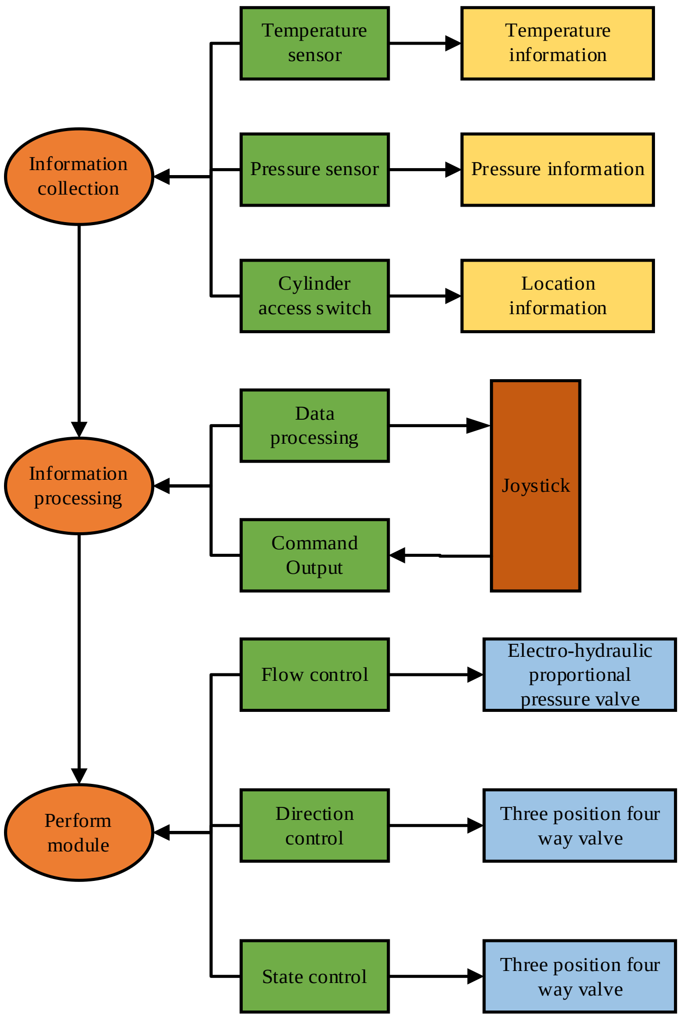
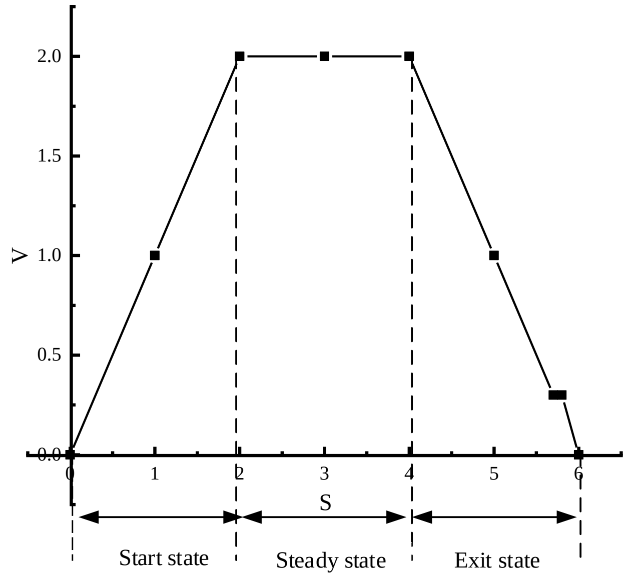


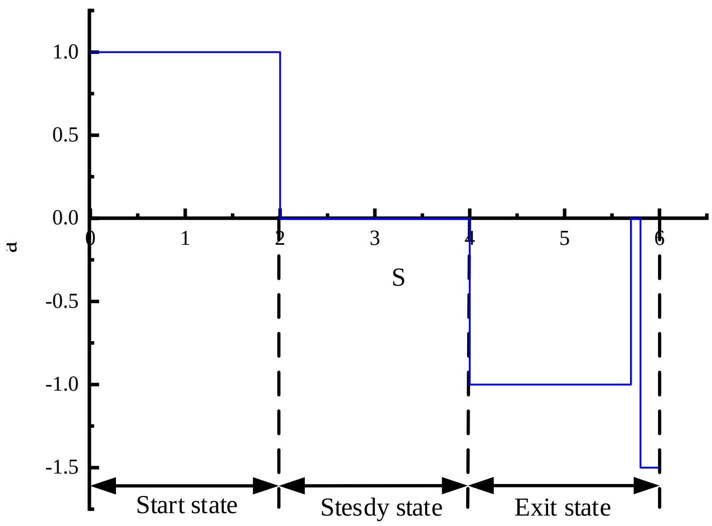
Figure 2: The overall design scheme of the control system of the manipulator

In the design of the control scheme, the motion process of the manipulator can be divided into three states. The first is the start state. In the start state, the manipulator performs a uniform acceleration motion. By increasing the opening of the electro-hydraulic proportional valve [10] and increasing the running speed of the cylinder piston, which can eliminate hydraulic shock, and accelerate the operation speed and save the time of operation. The second is the steady state. In this state, to save the operating time of the manipulator, the manipulator is generally moved at the highest speed and the most uniform speed to improve the efficiency of construction, and the uniform motion is realized by controlling the opening size of the electro-hydraulic proportional valve to remain unchanged.

The third is the end state. In this state, if the cylinder piston stops suddenly, it may cause the manipulator to vibrate violently and reduce the service life of the manipulator. To avoid this situation, in the end state, by controlling the opening of the electro-hydraulic proportional valve gradually decrease to make the manipulator do constant deceleration motion. When its speed is reduced to a certain value, the electro-hydraulic proportional valve will no longer decrease, and the manipulator will move at a low speed at a uniform speed. When the accuracy required for the positioning of the manipulator is achieved, then the manipulator does the deceleration motion until the motion stops. The speed change and acceleration change of the whole process are shown in Figure 3.



(a)The speed change of the manipulator in the process of the movement



(b)The acceleration change of the manipulator in the process of the movement

Figure 3: The speed and acceleration change of the manipulator in the process of the movement

2.3 Design of Fuzzy Controller of the Electronic Drive Control System of Hydraulic Joints of the Manipulator

The hydraulic electronic drive control system of the manipulator is a control system composed of a combination of hydraulic system and electronic drive system, and its composition is shown in Figure 4.

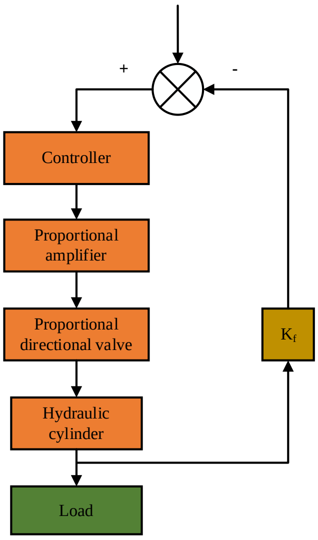


Figure 4: The hydraulic electronic drive control system of the manipulator

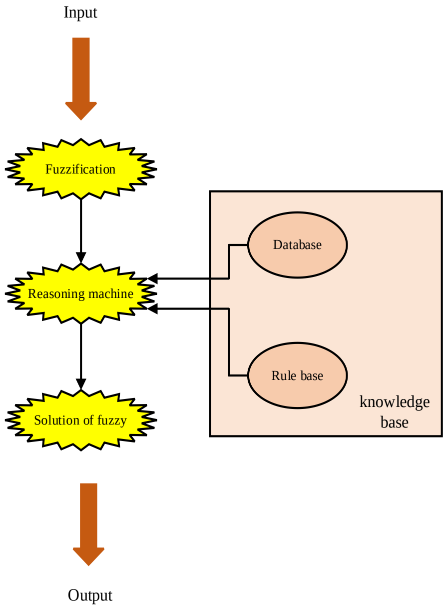
Compared with other systems, the hydraulic electronic drive system of the manipulator has the advantages of fast response, strong adjustment ability, and high control progress, and can control large inertia to achieve high-power output. When controlling the speed of the manipulator, the control of the movement speed of the oil cylinder is mainly realized by controlling the opening of the electro-hydraulic proportional valve to control the oil flow.

The control system of the manipulator arm of the jumbo is a nonlinear and complex system. The conventional PID control system [11] cannot meet the requirements of the manipulator control system of the jumbo. The fuzzy theory [12] is combined with the PID control method to adjust the parameters in real-time, give full play to the control function of the PID regulator, and can well adapt to the working requirements of the jumbo manipulator.

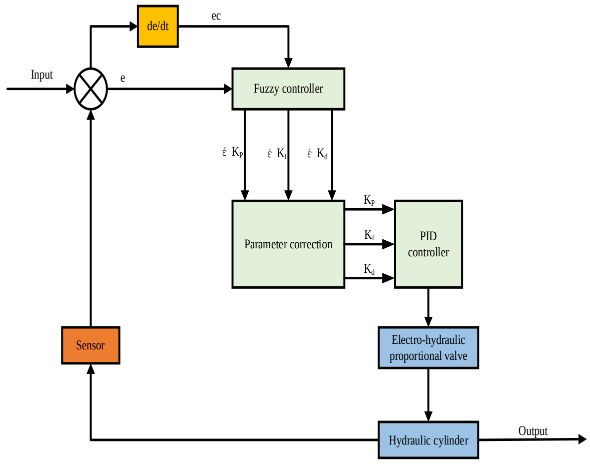
Compared with traditional control systems, the biggest difference between the fuzzy PID control system [13] is that the control center of the fuzzy control system is the fuzzy controller, which is divided into four parts: the fuzzy module, the inference module, the defuzzification module and the knowledge base.

In the fuzzy module, the precise value is blurred, and the precise value is converted into a fuzzy quantity, and then the fuzzy quantity is passed to the inference module for inference and judgment. At the blurred interface, there is generally a quantization factor. The knowledge base includes databases and rule bases. The database includes quantification factors, scale factors, and membership functions of linguistic variables. The rule base mainly contains control rules. The inference module judges the fuzzy quantity according to the control rules, and obtains the output quantity and conclusion, which is the core part of the controller. The defuzzification module is a part of clarifying the fuzzy quantities, and converts the control variables output by the inference module into precise control quantities.

The displacement of the hydraulic cylinder is mainly used as the control object. Therefore, the displacement deviation e of the hydraulic cylinder and the displacement deviation change rate ec are selected as the input, and the offset of the three parameters of the conventional PID controller K_P, K_I and K_d are still taken as its output. The composition and structure of the fuzzy PID controller are shown in Figure 5.



(a) The composition of the fuzzy PID controller



(b) The structure of the fuzzy PID controller

Figure 5: The composition and structure of the fuzzy PID controller

The fuzzy PID controller meets the requirements of the control system by adjusting the parameters of K_P, K_I and K_d in real-time. The expressions of the three parameters of K_P, K_I and K_d are shown in equations (1) to (3).

$$K_{P(k)} = K_P(k) + \Delta K_P \tag{1}$$

$$K_{I(k)} = K_I(k) + \Delta K_I \tag{2}$$

$$K_{d(k)} = K_d(k) + \Delta K_d \tag{3}$$

In equations (1) to (3), $K_P(k)$, $K_I(k)$,$K_d(k)$ represent the initial part. ΔK_P, ΔK_I, ΔK_d show the corrected part of the parameter, and the expression of the corrected part is shown in equations (4) to (6).

$$\Delta K_{P(k)} = K_{uP}\{e(k), ec(k)\}_P \tag{4}$$

$$\Delta K_{I(k)} = K_{uI}\{e(k), ec(k)\}_I \tag{5}$$

$$\Delta K_{d(k)} = K_{ud}\{e(k), ec(k)\}_d \tag{6}$$

Generally, the input variables are blurred by determining the fuzzy subsets on the fuzzy domain [14]. The greater the number of fuzzy subsets, the higher the accuracy of fuzzy control, but the greater the number of fuzzy subsets, the greater the computational time and the larger the amount of computation of the inference module. Therefore, the number of fuzzy subsets is generally controlled between 3 and 9. The number of fuzzy subsets for displacement deviation e and displacement deviation change rate ec is 7.

The membership function [15] is used to represent the relationship between fuzzy values and fuzzy sets in the domain. The membership function is a representation of the continuity, stability, and gradual change of things, reflecting the objective reality of things. Common membership functions include triangular, trapezoidal, Gaussian, Sigmoid, etc. [16]. The triangular membership function is selected to control the variable proportional coefficient K_P, integral coefficient K_I, and differential coefficient K_d. Its function expression is shown in equations (7):

$$f(x,a,b,c) = \begin{cases} 0 & x \le a \\ (x-a)/(b-a) & a \le x \le b \\ (c-x)/(c-b) & b \le x \le c \\ 0 & x \ge c \end{cases} \tag{7}$$

In the equation, a, b and c are the parameters to determine the shape of the function.

For displacement deviation e and displacement deviation change rate ec, the Gaussian membership function is selected, and the function expression is shown in equation (8):

$$f(x,\delta,c) = e^{\frac{-(x-c)^2}{2\delta^2}} \tag{8}$$

c and δ are both parameters to determine the shape of the function

In fuzzy control, the basic domain of input variables is the variation range of the input variables of the control system. The universes of displacement deviation e, displacement deviation change rate ec, proportional coefficient K_P, integral coefficient K_I, and differential coefficient K_d are respectively defined, as shown in equation (9):

$$\begin{cases} e = \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\} \\ ec = \{-3,-2,-1,0,1,2,3\} \\ K_P = \{-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6\} \\ K_I = \{-3,-2,-1,0,1,2,3\} \\ K_d = \{-3,-2,-1,0,1,2,3\} \end{cases} \tag{9}$$

To better fuzzy control the system, the quantization factor is usually used to convert the value in the basic domain into the coefficient in the fuzzy domain, assuming that the basic domain is $X_j = [-x, x]$, and the fuzzy domain is $N_j = [-n, n]$, the calculation of the quantization factor is shown in equation (10):

$$K = \frac{n}{x} \tag{10}$$

However, in practical applications, the scope of the basic domain and the fuzzy domain are usually inconsistent, so it is necessary to limit the scope of the basic domain, as shown in equation (11).

$$n = \begin{cases} n, & Kx \ge n \\ Kx, & Kx < n \\ -n, & Kx \ge -n \end{cases} \tag{11}$$

To meet the requirements of the output and input in the system, the quantization factor is selected: K_e=K_{ec}=0.01.

In the process of defuzzification, the fuzzy quantity can be converted into a clear value through the scale factor. Assuming that the fuzzy domain is $M = [-m, m]$, the variation range of the control quantity required by the actuator is $Y = [-y, y]$, the calculation of the scale factor is shown in equation (12):

$$K_b = \frac{y}{m} \tag{12}$$

The scale factor is selected as K_1=60, K_2=0.5, K_3=0.5 to meet the control requirements of the system.

Fuzzy control rules are the most critical part of the fuzzy controller. The establishment of fuzzy control rules generally includes three steps. Firstly, the variable word set is determined. Secondly, the fuzzy subset is defined. Finally, the fuzzy rules are established.

Firstly, the variable word set is determined. There are five variables in the system, namely e, ec, K_P, K_I and K_d. The variable word set is shown in Table 1.

Table 1: The variable word set of fuzzy control rules

Negative Big	Negative Medium	Negative Small	Zero	Positive Small	Positive Medium	Positive Big
NB	NM	NS	ZO	PS	PM	PB

Secondly, the fuzzy subset is defined. The shape of the membership function of the fuzzy subset is determined. To obtain the fuzzy subset, the membership function is discretized.

Finally, the fuzzy rules are established, and the fuzzy rules are shown in Table 2.

Table 2: The fuzzy control rules

$K_P/K_I/K_d$		ec						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/NM	ZO/ZO/PS
	NM	PB/NB/PS	PB/NB/NS	PM/NM/NB	PS/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/ZO/ZO
	NS	PM/NB/ZO	PM/NM/NS	PM/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/NS	NS/PS/ZO
	ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NM/PM/NS	NM/PM/ZO
	PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	NS/PS/ZO	NM/PM/ZO	NM/PB/ZO
	PM	PS/ZO/PB	ZO/ZO/NS	NS/PS/PS	NM/PS/PS	NM/PM/PS	NM/PB/PS	NB/PB/PB
	PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PM	NM/PM/PS	NB/PB/PS	NB/PB/PB

2.4 The Overall Design of Hardware System of the Electronic Drive Control System of the Hydraulic Joints of the Manipulator

The hardware circuit system is the basis for the stable and efficient operation of the electronic drive control system of the hydraulic joints of the manipulator. The accurate processing of the signal is the key to the realization of the system. Simultaneously, the design of hardware also provides the basis for the development of the control system software.

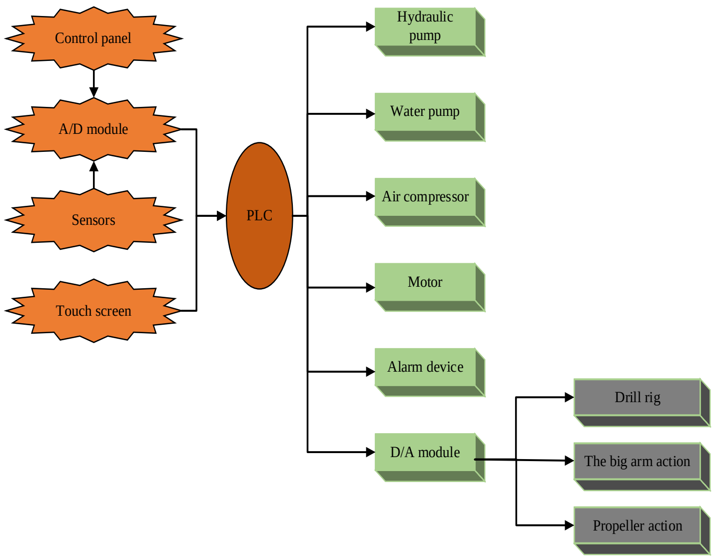
The hardware part of the electronic drive control system of the hydraulic joints of the manipulator is mainly composed of the minimum system circuit of the main control chip, the power supply circuit, the information acquisition circuit, the drive control circuit, the conversion circuit of the Digital to Analog Converter (D/A), the conversion circuit of the Analog to Digital Converter (A/D), a memory circuit and communication circuit. Combining these parts on the same circuit board according to the functions required by different controllers is conducive to the development and debugging of the hardware in the later stage.

The information acquisition circuit of the motion controller in the rear arm is mainly to collect the motion information of the hydraulic cylinder tensile sensor of the arm and the two rotary encoders of the joint. The expansion of the hydraulic cylinder of the arm is mainly controlled by the driving control circuit to control the electromagnetic reversing valve. The information acquisition circuit in the controller in the middle arm extender is mainly to collect the movement forms of the extension cylinder tensile sensor. The expansion of the extension cylinder is realized by controlling the electromagnetic reversing valve through the driving control circuit. The information acquisition circuit in the forearm motion controller mainly collects the motion information of the pull rope sensor of the pitch hydraulic cylinder and the two rotary encoders of the joint, and the expansion of the pitch hydraulic cylinder is also realized by controlling the electromagnetic reversing valve through the drive control circuit. Besides, there is the motion controller of the propulsion beam, and its information circuit mainly collects the information of the external swing and compensation hydraulic cylinder pull-rope sensor and the rotary encoder of the overturning hydraulic motor. The hydraulic pump controller includes the A/D conversion circuit and the D/A conversion circuit. The former collects the pressure information of the pump station, the latter adjusts the output frequency of the inverter, and the start and stop of the inverter is controlled by the drive control circuit

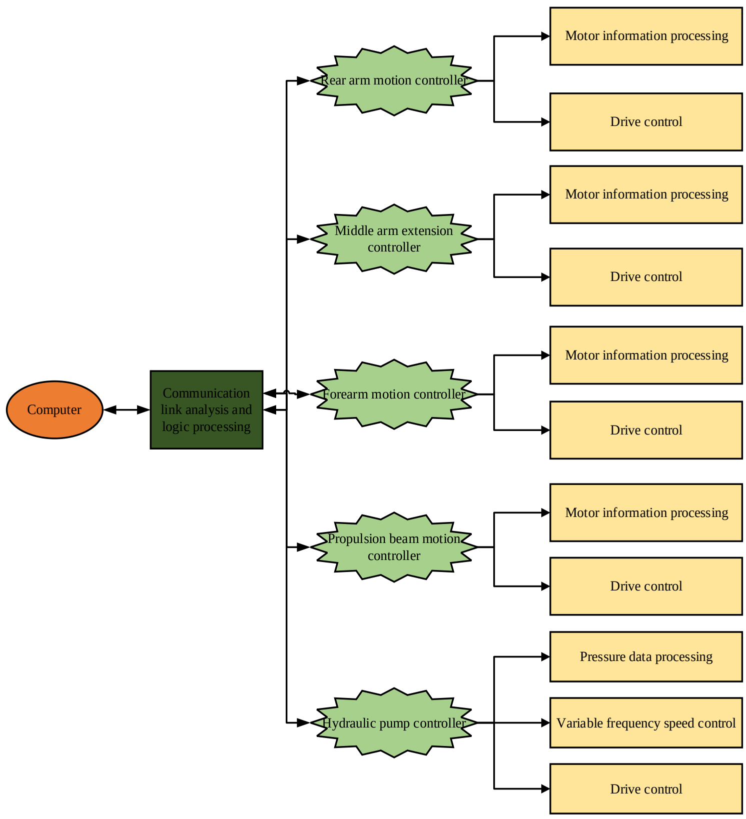
Moreover, the hardware system also includes a power supply circuit that enables the controller to operate stably, a communication circuit that enables the controller to communicate with the computer, and a memory circuit that stores the operating status of the system.

In the whole control system, besides the hardware system, the design of the software system is also an important part.

In the process of software design, the work that each controller needs to complete should be clearly defined first, and then the software design of each controller should be carried out. For each motion joint controller, there are mainly motion information processing and drive control modules, among which the motion information processing module is responsible for data processing of the information collected by the sensor, and the drive control module mainly completes the start-stop and expansion control of the joint. For the hydraulic pumping station controller, there are mainly pressure data processing, frequency conversion speed control and drive modules, among which the pressure data processing module processes the pressure information in the main oil circuit, the frequency conversion speed control module is responsible for the adjustment and control of the hydraulic pump, and the drive control module is responsible for controlling the working status of the hydraulic pumping station. In addition, each controller also has a communication module, which realizes communication with computers through communication link analysis and logical processing. The diagram of the overall design of its hardware system and software system is shown in Figure 6.



(a) The diagram of the overall design of hardware system of the electronic drive control system of the hydraulic joints of the manipulator



(b) The diagram of the overall design of software system of the electronic drive control system of the hydraulic joints of the manipulator

Figure 6: The diagram of the overall design of the hardware system and software system of the electronic drive control system of the hydraulic joints of the manipulator

3. Simulation Experiment and Result Analysis

3.1 The Setting of Simulation Experiment of PID Controller

The Graphical User Interface (GUI) method of the Simulink simulation module in MATLAB (Matrix Laboratory) is used to simulate. Enter the fuzzy command in the command window of MATLAB to open the FIS editor, and then set the fuzzy inference system and fuzzy logic algorithm respectively, as shown in Figure 7.

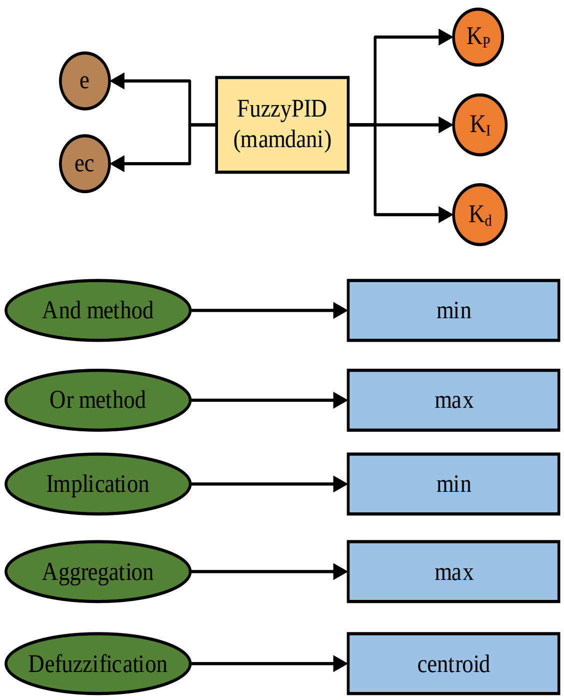
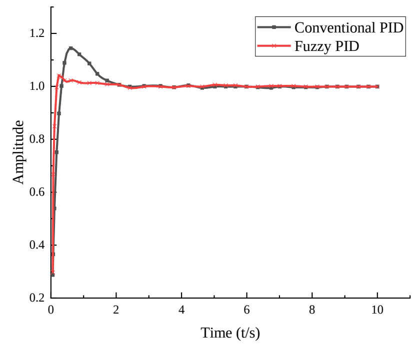


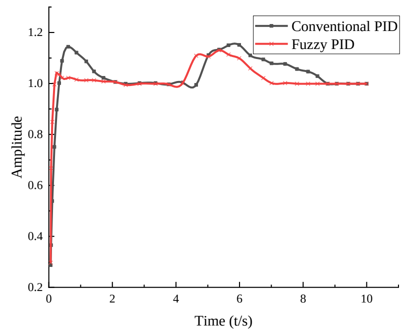
Figure 7: The setting of fuzzy inference system and fuzzy logic algorithm

After setting the fuzzy inference system and the fuzzy logic algorithm, the fuzzy logic rules can be set. The specific content is shown in Table 2. The "if and then" statement is used to set. After that, the complete fuzzy rule observation window and output surface observation window can be viewed. The surface is smooth, indicating that the design value of the input and output is reasonable. After the fuzzy logic inference system is set, the simulation model can be established.

The simulation is carried out in the simulation model diagram of the established fuzzy controller, and the simulation results of the conventional PID controller and the fuzzy PID controller are studied when the external load is disturbed. The results are shown in Figure 8.



(a) Comparison of fuzzy PID and conventional PID without interference of external load



(b) Comparison of fuzzy PID and conventional PID when impacted by 10000N external load

Figure 8: Simulation comparison of fuzzy PID and conventional PID

Figure 8 indicates that the rise time of the fuzzy controller is only about 0.3s, while the rise time of the conventional PID controller is about 1s. The rise time of the fuzzy PID controller is significantly smaller than that of the conventional PID controller. The overshoot is significantly smaller than that of the conventional PID device, and the system generates little vibration and can quickly become stable. The stabilization time of the two controllers is basically 2s, and the steady-state error is 0. When impacted by an external load of 10000N, the fuzzy PID controller responds faster, the amplitude of the highest peak value is about 1.13s, and the adjustment time is about 3s, but the amplitude of the highest peak value of the conventional PID controller is about 1.15s, and the adjustment time is about 3.8s, which shows that the fuzzy PID controller has stronger tamper-resistance ability, better dynamic performance and more stable than the conventional PID controller when it is impacted by the external load.

4. Conclusions

The use of the jumbo has brought great convenience to underground construction such as rock tunnels, promotes the development of modern tunnel construction, improves the working environment of workers underground tunnel construction, and provides a guarantee for their safety.

Firstly, the working process of the jumbo and the structure of the manipulator of the jumbo are studied. Secondly, the controller of the electronic drive control system of the hydraulic joints of the manipulator is designed by the method of fuzzy PID control. The hardware and software parts of the electronic drive control system of the hydraulic joints of the manipulator are designed as a whole. Finally, the simulation experiment of the constructed fuzzy PID controller is carried out by using MATLAB software.

The experimental results show that the rise time of the fuzzy PID controller is significantly smaller than that of the conventional PID controller, and the vibration generated by the system is small, which can quickly stabilize. When impacted by an external load of 10000N, the response time of the fuzzy PID controller is faster. The highest peak value of the amplitude change after the impact is 1.13s, and the adjustment time is 3s. Compared with the conventional PID controller, its tamper-resistance ability is stronger and the dynamic performance is better. The results provide research experience for further improving the efficiency of tunnel construction through a computer-controlled manipulator of the jumbo, which is of great practical significance. There are still great shortcomings in the research. When designing fuzzy PID controllers, the selection of domains, quantization factors and proportional factors is too dependent on a lot of work experience, and there are still obstacles to the use of inexperienced people. In subsequent studies, fuzzy PID control will be further optimized from this aspect.

Acknowledgement

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