Hydraulic Pan-tilt Servo Control System Based on Hydraulic Actuator Model

Kaihao Zhang, Xuewen Rong*, Kun Yang, Yibin Li
School of Control Science and Engineering, Shandong University
Jinan, Shandong Province, China
Email:scrobot@163.com

Hui Chai
School of Mechanical Engineering, Shandong University
Jinan, Shandong Province, China
Email:pigging.chai@gmail.com

***Abstract*—In order to achieve the unmanned live cleaning operation in the substation, and ensure the running trajectory and control precision fulfil requirements, a hydraulic pan-tilt control system based on hydraulic actuator model is designed. The pan-tilt reaches a certain location with a certain speed is the main purpose of control. In this paper, the movement of the pan-tilt is based on the model of the hydraulic actuator and the position-speed-position three loops controller. The experimental results show that the hydraulic servo control system has good accuracy, good reliability, good load-bearing capacity, fast response. It verifies the effectiveness of the control method.**

I. Introduction

Pan-tilt is a complex combination of the photoelectric equipment carrier, and it is used to carry high-precision equipment. It can not only stabilize the equipment, but also increase the degree of freedom of equipment, as well as expand the work space. In essence, the pan-tilt is a category of small and medium-sized turntable, which can be driven by the motor, pneumatic, hydraulic or combined of various forms [1]. The purpose of the study is to control the two-degree-of-freedom high-precision positioning pan-tilt, referred to as 2-DOF pan-tilt, which contains of pitch and yaw two degrees of freedom [2].

The traditional pan-tilt is used for camera, photography and astronomical observation. It has a complex structure and a small speed range, and need a man to operation directly, which is inconvenience. The pan-tilt designed in this word can achieve automatic operation through the control command, which can increase its control accuracy and speed range.

At present, most of the high-performance automatic pan-tilt on the market are motor drive [1], [3]–[9] and are widely used in monitoring [1], [3], [5], inspection [4], unmanned plane [6], [7] and so on.

Hydraulic pan-tilt has its own disadvantage, which needs high system maintenance requirements and cost more for hydraulic components manufacturing. However, in a complex and harsh environment like substation with high-intensity electromagnetic radiation, comparing with electric pan-tilt, the hydraulic pan-tilt has the following advantages: (1)hydraulic oil has a non-conductive characteristic, therefore, the use of hydraulic pan-tilt in substation is more secure and reliable; (2)even if in the water state, the hydraulic pan-tilt can still work properly; (3)use hydraulic oil as the driving, can increase the service life of the system. Hence the hydraulic pan-tilt is chosen.

In this paper, using the experience of the design of the electric pan-tilt control system [1], [3], [4], [8], [9], the DSP-TMS320F28335 is chosen as the core microcontroller to control the hydraulic pan-tilt.

II. System structure and characteristics

A. Introduction of the Hydraulic Mechanical System

The pan-tilt body is compact and strong, which can adapt to harsh environments. It has IP67 protection level and small size, as well as weight-bearing ratio of about 1: 1.5. Its yaw operating range of $-90°$ to $90°$, and pitch operating range of $-30°$ to $+70°$. Figure 1 shows the pan-tilt body.

Fig. 1. Pan-tilt body

The hydraulic system uses an electrically driven hydraulic pump as the energy device. Its principle is using the hydraulic oil to change the mechanical energy of the prime mover into the hydraulic force energy. The flow and direction of the hydraulic oil is changed by the valve, and the speed and direction of pan-tilt can be controlled. The accumulator can absorb hydraulic shock to ensure that the entire system pressure normally, and make the system stability.

B. Introduction of the Circuit Control System

The overall block diagram of the control system is shown in Figure 2. The core of DSP controller is TMS320F28335 microcontroller, mainly for hydraulic pan-tilt mobile servo control. This controller reads the feedback value from absolute encoder and can receive the control commands from the host computer or the serial debugging assistant. After calculation,

978-1-5386-3524-7/17/$31.00 ©2017 IEEE

the control signal of each servo valve is obtained, and then used to control the current of servo valve. Due to the current is changed, the hydraulic pan-tilt can move. The host computer can receive the feedback signal from the DSP controller and the encoder and display them to the operator.

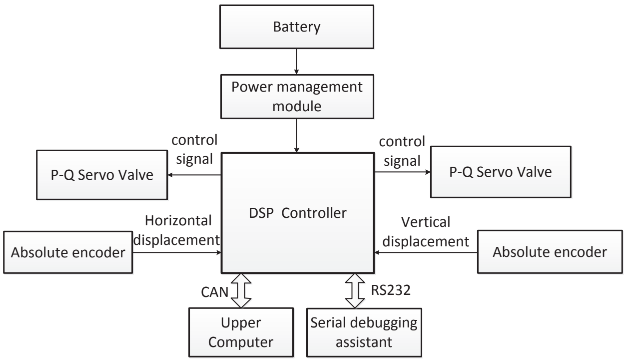

Fig. 2. Overview of Hydraulic PTZ Control System

III. Hardware Design and Implementation

Photoelectric isolation, adding multiple filters and reasonable component layout are used to ensure the reliable operation of the circuit and reduce the signal interference. Therefore the hydraulic pan-tilt system is able to work in the environment of electromagnetic interference, and stably for a long time. The following descriptions are the main part of the hardware system.

A. DSP Microcontroller

The core microcontroller used in this system is TMS320F28335, which is produced by TI company. Compared with the previous DSP, the device has high precision, low cost, low power consumption, high peripheral integration, data and program storage capacity, A / D conversion more accurate and fast features [10].

B. Absolute encoder

The system uses the R22-SER 12-bit absolute encoder. It has protection class of IP65, which can combat interference effectively. It has independent linear accuracy of 0.3%, and the response speed of 0.38ms, which make it can meet the position accuracy and response speed needed by the system.

C. Communication and power supply

The communication system uses RS232 serial port and CAN communication at the same time, while the power supply is selected to use 24V external voltage. The internal voltage is realized by the power supply module.

IV. Software design

The system takes the efficiency and maintenance of software development into consideration, hence a modular structure is designed. TI's CCS software is used as a development tool, and the code is written using C / C ++ language. Software design includes the system functions and the host computer communication.

A. System functions

In order to achieve live cleaning and other requirements, the main functions of the hydraulic pan-tilt control system are: (1) continuous movement in the yaw (pitch) direction; (2) position servo in the yaw (pitch) direction; (3) scan movement in both directions; (4) motion information and motion status query; (5) reach a certain location with a certain speed, and the speed can be adjustable.

B. Host computer communication

In order to make use of system functions more convenient, a custom protocol based on the Pelco-D protocol is designed [11]. The operator can control the movement of the hydraulic pan-tilt according to the protocol through the serial transmission control command. At the same time, in order to collect the feedback data real-time, CAN communication is also designed. Therefore, this system can not only through the serial port to send instructions and receive data, but also can send instructions through the CAN and real-time display pan-tilt motion status.

V. Hydraulic actuator model and motion control algorithm

A. Hydraulic actuator model

Hydraulic actuator consists of flow servo valve and screw rotary cylinder. Screw rotary cylinder is a kind of hydraulic components that converts the linear motion of a piston into a rotary motion, which are widely used in high torque limited swing motion places. With the action of the two-stage screw pair, the piston in the rotating sleeve moves linearly and rotates along the spiral by adjusting the oil pressure difference between the inlet and outlet ports. The output shaft driven by the screw rod also rotates, hence the swing motion can be achieved. And in the two-stage spiral sub-amplification, as long as the smaller working stroke, a large output rotation angel can be obtained [12], [13]. Zhang has proposed a straight hydraulic cylinder model [14]. Experimental studies have found that the analysis of the straight cylinder can also be applied to the screw rotary cylinder, but some changes still need to be made. Figure 3 shows the hydraulic actuator model.

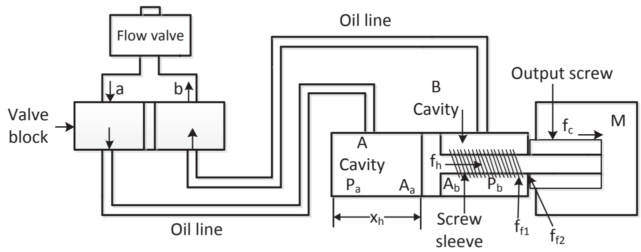

Fig. 3. Hydraulic actuator model

Most of the analysis of the model can be obtained from the literature [14], where the main description is the different of the screw rotary cylinder and linear cylinder.

It can be clearly seen from the figure that the screw rotary cylinder increases the internal rotational friction with respect to the linear cylinder, due to increasing the frictional force, the output force f_c of the hydraulic actuator acting on the load is:

$$f_c = f_h - f_{f1} - f_{f2} \tag{1}$$

where f_h is the hydraulic pressure, f_{f1} is the rotational friction force, f_{f2} is the friction between the piston and the cylinder. Other analysis mentioned in the literature, will not repeat here.

For the hydraulic actuator position servo, the hydraulic cylinder force balance equation is:

$$A_1P_a - A_2P_b = M\frac{d^2y}{dt^2} + B\frac{dy}{dt} + K_y y + F \tag{2}$$

M is the total mass of the piston and the load, B is the viscous damping coefficient between the piston and the load, K_y is the amplification factor, and F is the external force acting on the piston. Therefore, when $F = 0$, the characteristics of the hydraulic actuator is the core of the entire position servo system. Some experiments had been done when $F = 0$, based on the literature [15], [16] and experiments, the block diagram of the system is obtained and shown in Figure 4.

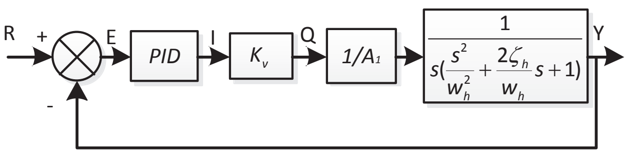

Fig. 4. $F = 0$ Hydraulic actuator position servo block diagram

In the figure, K_v is the flow gain, w_h is the natural frequency of the hydraulic, ζ_h is the hydraulic damping ratio, and A_1 is the cross-sectional area of the piston in the rodless cavity. As the hydraulic cylinder in different positions the hydraulic natural frequency is different, generally take the lowest natural frequency to calculate. Data obtained from experiments, hence the transfer function can be obtained in this hydraulic system:

$$\frac{Y}{R} = \frac{145.5}{\frac{s^3}{4257.9^2} + \frac{s^2}{21379.5} + s} \tag{3}$$

Figure 5 and Figure 6 show the above analysis.

Through the figure it can be concluded that when $F = 0$ the system open-loop and closed-loop are stability, the parameters chosen in this system are suitable.

When $F \neq 0$, The control chart of the whole system is shown in Figure 7.

In Figure 7, K_c is the flow-pressure gain, β_e is the equivalent volume elastic modulus of the hydraulic oil, and V_t is the valve voltage at time t.

Through the subsequent experiment, it can be concluded that even if $F \neq 0$, the whole system is still stable and reliable, and can respond in a timely manner. It is shown that the actuator model, the servo block diagram and the selected parameters used in this paper can reflect the characteristics of the hydraulic system effectively.

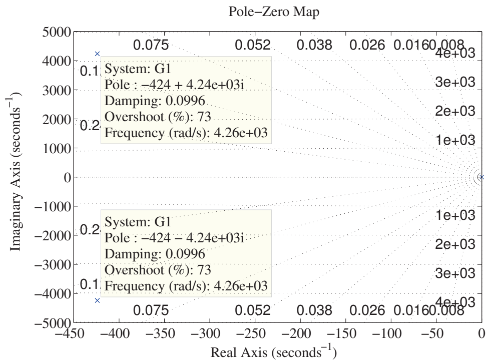

Fig. 5. Pole-Zero Map

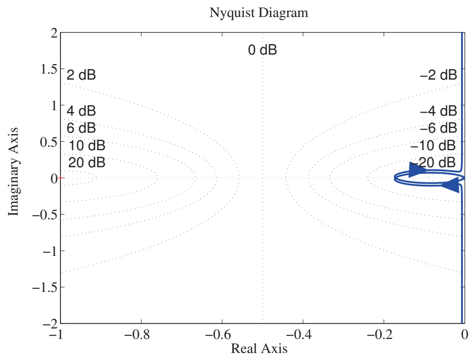

Fig. 6. Nyquist Diagram

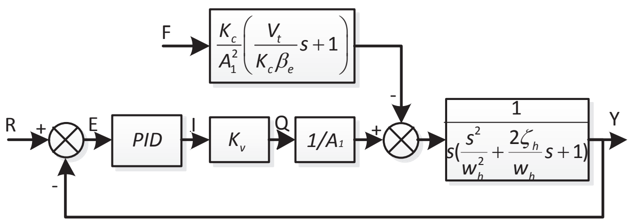

Fig. 7. $F \neq 0$ Hydraulic actuator position servo block diagram

B. Pan-tilt motion control algorithm

In order to realize the main function of the system, a three-loop control system of position-velocity-position is used, which is mainly used to control the position and the speed of pan-tilt. This tricyclic loop can be used separately: the speed-position loop is taken out separately to achieve simple speed control. When there is no given speed, the outermost position loop can also achieve position control, hence the pan-tilt can reach the desired location. When using the tricyclic control, the pan-tilt can reach a certain location with a certain speed. Figure 8 shows the control algorithm.

For this control system, in order to eliminate the steady-state error, and improve the system control accuracy, a segmented PID control strategy is used.

$$Ref - \epsilon < Feedback < Ref + \epsilon \tag{4}$$

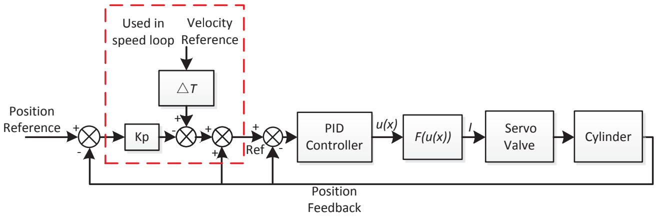

Fig. 8. Motion control algorithm

When the position feedback value is within $\pm\epsilon$ of the given value, the second set of PID parameters is used, otherwise the first set of PID parameters are used, where ϵ is the individual set deviation value.

VI. Practical Experiment

Three different experiments had been done and the movement state of the pan-tilt was recorded.

(1) Make the pan-tilt move back and forth between two invariant angles and observe the stability and positioning accuracy of the pan-tilt. These are shown in Figure 9 and Figure 10.

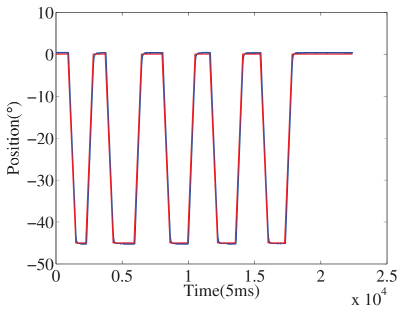

Fig. 9. Large-scale positioning

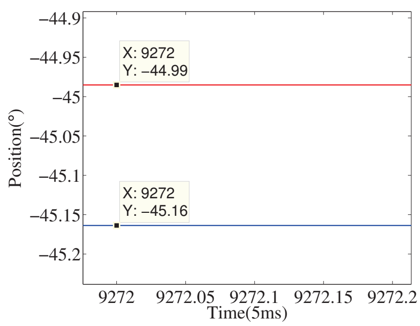

Fig. 10. Positioning accuracy

(2) Making pan-tilt at different speed in the range of $\pm 90°$ movement, the state of motion is shown in Figure 11.

(3) Using sine wave with different frequency and different amplitude as reference, observe the pan-tilt servo effect, the effect is shown in the Figure 12, Figure 13, Figure 14, Figure 15, Figure 16.

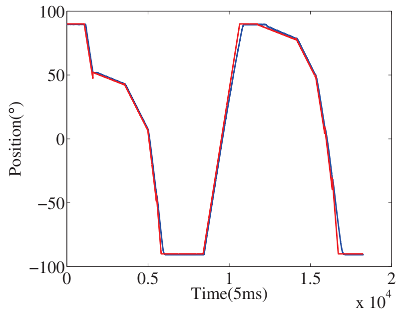

Fig. 11. Variable speed movement

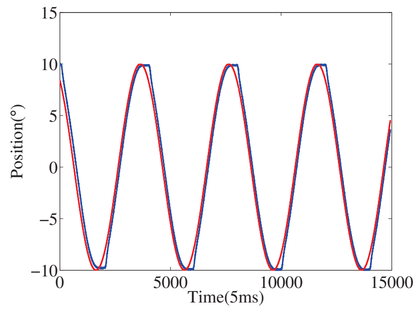

Fig. 12. 0.05Hz $\pm 10°$;

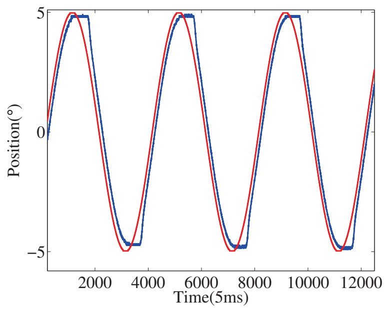

Fig. 13. 0.05Hz $\pm 5°$;

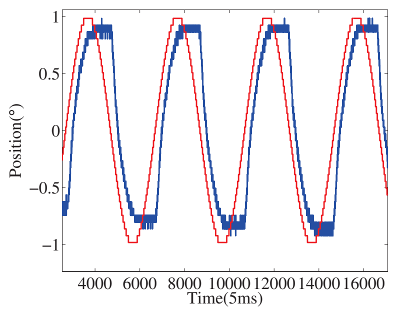

Fig. 14. 0.05Hz $\pm 1°$;

The two directions of movement are the same, so only the yaw movement state is listed here. In the figure, red is the given value and blue is the feedback value. The experimental results show that the whole hydraulic pan-tilt control system is stable and has high positioning accuracy of 0.17°. It can

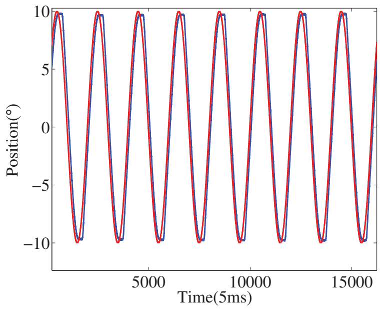

Fig. 15. 0.1Hz $\pm 10°$;

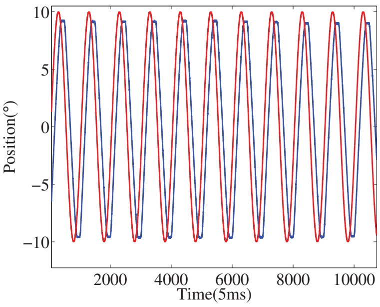

Fig. 16. 0.2Hz $\pm 10°$;

realize the variable speed movement and the speed can be adjusted at any time. It can be timely response and stable servo in the frequency below 0.2Hz and small amplitude variation range.

But when the frequency raised to 1Hz, the servo ability would be significantly worse, and can only reach 1/4 given value. The data is not shown here, however, through several experiments and further studies can be concluded that the response frequency can not be further improved because of the two parts: (1) due to the tubing is thin and flow rate is slowly, after the frequency of the servo valve responds is improved, the hydraulic oil entering the spiral hydraulic cylinder is reduced. At the same time, the pipe is long, in the hydraulic oil transmission process, the pressure loss is big along the way. Therefore the piston moves slowly and the pan-tilt can not achieve effectively control in the fast sinusoidal movement; (2) hydraulic actuator model is not accurate, resulting in deterioration of the control effect after frequency increase.

VII. Conclusion

In the special work environment of the substation, through assembly of the water gun, the pan-tilt can be very convenient to achieve live cleaning function. It can reduce the use of manpower greatly, hence the human can work as little as possible in the dangerous environment, to ensure the safety of personnel. Therefore, the study of hydraulic pan-tilt has practical and more of a very important significance.

In this paper, the hydraulic pan-tilt control system is introduced from the aspects of system structure, hardware design, software design, actuator model and control algorithm. It shows that the control system is simple in structure, reliable in operation and can communicate in many ways.

Experiments show that this pan-tilt control system has accurate positioning and speed adjustable features, and can realize the function of the high-performance pan-tilt system on the market. It can be used not only for live cleaning, but also in automatic driving, mobile robot and other fields, with good market prospects.

Acknowledgment

The authors would like to thanks Aizhen Xie for her great support in this hydraulic pan-tilt.

This work is partially supported by the National High Technology Research and Development Program of China.[Grant No.2015AA042201].

References

[1] Xiaojie Fu. *Research on the Mechanical Structure and Control System of a High Precision Servo Pan-tilt Turntable*. PhD thesis, Zhejiang University, 2014.

[2] David W Murray, Philip F McLauchlan, Ian D Reid, and Paul M Sharkey. Reactions to peripheral image motion using a head/eye platform. In *Computer Vision, 1993. Proceedings., Fourth International Conference on*, pages 403–411. IEEE, 1993.

[3] Yifei Wu, Sheng LI, and Hua Cai. Design and implementation of pan-tilt control system based on msp430 mcu. *Microcomputer Information*, (07Z):90–93, 2006.

[4] Peng Xiao, Haipeng Wang, Lei Cao, Mingrui Wang, Daqing Sun, Tao Cao, et al. Controi system design of ptz for intelligent substation equipment inspection robot. *Manufacturing Automation*, (2012 year 01):105–108, 2012.

[5] Hong Zheng and Zhenqiang Liu. Self-calibration of pan-tilt camera based on accurate model. *Robot*, 35(3):326G331–338, 2013.

[6] Xiangqing Li, Xiuxia Sun, Jianliang Peng, and Xinli Zhou. Motion compensation based gimbal controller design for small uav. *Systems Engineering and Electronics*, 33(2):376–379, 2011.

[7] Rijun Wang, Yue Bai, Zhijun Xu, Changjun Zhao, Xin Zhang, and Yantao Tian. A composite disturbance compensation method for airborne platform based on improved disturbance observer. *Journal of OptoelectronicsLaser*, 26(1):108–115, 2015.

[8] Wei Zhang, Huaiyu Wu, Lei Cheng, Linping Hu, and Heng Fang. A 2-dof robot pan-tilt platform based on dsp. *Techniques Of Automation And Applications*, (3):107–109, 2009.

[9] Linping Hu. *Design and Implementation of 2-DOF Pan-Tilt with Integrated Drive-serve Controller Based on DSP*. PhD thesis, Wuhan University of Science and Technology, 2008.

[10] Qingjie Zhang, You Xu, Nan Zuo, et al. Hand to teach you to learn dsp - based on tms320f28335, 2015.

[11] Yingyu Lu and Yonglin Zhang. Implementation of remote control on pan /tilt /zoom based on java. *Journal of Engineering Design*, 14(4):324–328, 2007.

[12] Songbai Li, Yilun Liu, Shiguan Xie, and Weitao Liu. Modeling and dynamic simulation of rotatoy hydraulic cylinder based on pro/e and adams. *Journal of Mechanical Transmission*, 2010.

[13] Songbai Li, Yilun Liu, and Weitao Liu. Optimal design for screw rotary cylinders radial clearance. *Journal of Central South University (Science and Technology)*, 43(5):1710–1716, 2012.

[14] Guoteng Zhang. *Research on Active Compliance and Trotting Gait Control of a Quadruped Robot*. PhD thesis, Shandong University, 2016.

[15] Linglong Li, Bin Sun, and Qifeng Zhang. Model and simulation analysis of asymmetrical hydraulic cylinder controlled by servo-valve. *Coal Mine Machinery*, 32(10):89–91, 2011.

[16] Dongguang Xu, Shenglin Wu, Keding Zhao, and Haijin Li. The theoretical analysis and experimental study about the position servo system of valve controlled single-rod cylinder. *Chinese Hydraulics and Pneumatics*, (6):35–39, 2005.