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COORDINATION AND DRIVE CONTROL SYSTEM FOR THE SIX DEGREE OF FREEDOMS MOTION PLATFORM

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Abstract. *This paper proposes a design method based on the idea of distributed control architecture and the design theory of fieldbus control system (FCS) for the control system of the six degree of freedoms (DOFs) motion platform, and the control scheme of the 6-DOFs motion platform based on the hinge space is completed. The ideal of layered design is applied to the prototype, and the whole system is divided into coordination layer and driver layer. The driver layer uses self-developed dedicated servo drives to achieve the driver servo, and an integral separation PID control algorithm is adopted by the closed-loop control algorithm for electric cylinder, and this algorithm can decrease the overshoot and improve the control performance. In coordination layer, an industrial Ethernet-CAN bus gateway is designed as a carrier, in order to increase the reliability of the CAN bus by giving it a redundant design, and also transplant real-time operating system μC/OS-II and TCP/IP protocol stack. Finally, a single electric cylinder control experiment and servo drive communication experiment with Ethernet-CAN bus gateway are carried out. The results verify that the control system meets the requirements and give a new solution to the control system of the 6-DOFs motion platform.*

Keywords: 6-DOFs motion platform, Distributed control technology, Servo control, Real-time operating system, TCP/IP stack

1. **Introduction.** 6-DOFs motion platform is a closed parallel mechanism formed by six actuators, through the cooperation of the six actuators, 6-DOFs motion platform can achieve translation, rotation and compound motion in the three-dimensional space.

At present, 6-DOFs motion platform research status is mainly concentrated in three aspects: kinematics, control strategy and drive mode. The research of kinematics is divided into two aspects: positive kinematics and inverse kinematics. The scholars in Harbin Institute of Technology used the numerical iteration based on Newton-Raphason method [1] to analyze the deviation transmission laws and provided the deviation transmission model and received higher precision results [2]. Boudrea summed up the kinematics positive algorithm by using genetic algorithm [3]. However, the solution generated by these algorithms is singular, and the freedom of 6-DOFs motion platform can be changed in a moment at the singular point, which can cause the system to lose control and the stiffness seriously decay. In the control strategy, Takegaki and Arimoto proved the stability of the PD controller of 6-DOFs motion platform by utilizing the idea of the control strategy of the series mechanism [4]. Seddgh and Horowitz invented the enhanced PD controller. However, these controllers are not well designed to overcome the effects of parameter time-varying and load disturbances [5].

In order to overcome the above problems, get a high-precision and high-reliability 6-DOFs motion platform. This paper proposes a design method based on the idea of distributed control architecture and the design theory of FCS for the control system of the 6-DOFs motion platform and the control scheme of the 6-DOFs motion platform based on the hinge space is accomplished, and the whole system is divided into coordination layer and driver layer. In order to improve the reliability and control performance of the system, a redundant design is adopted and the closed-loop control algorithm is improved. The experimental results show that the control system can meet the operating requirements, and give a new solution to the control system of the 6-DOFs motion platform.

2. **Overall Design of 6-DOFs Motion Platform Coordination and Drive Control System.** For the control system design of the 6-DOFs motion platform, this paper adopts the control system based on the hinge space, as illustrated in Figure 1, this will regard the six actuators of the 6-DOFs motion platform as independent systems and operate them respectively. Based on the hinge space, the stated position can receive each actuators drive rod expansion through the inverse solution. By using the corresponding displacement sensor to measure the each actuator's actual expansion amount, then compare it with the result received by inverse solution to command the difference value.

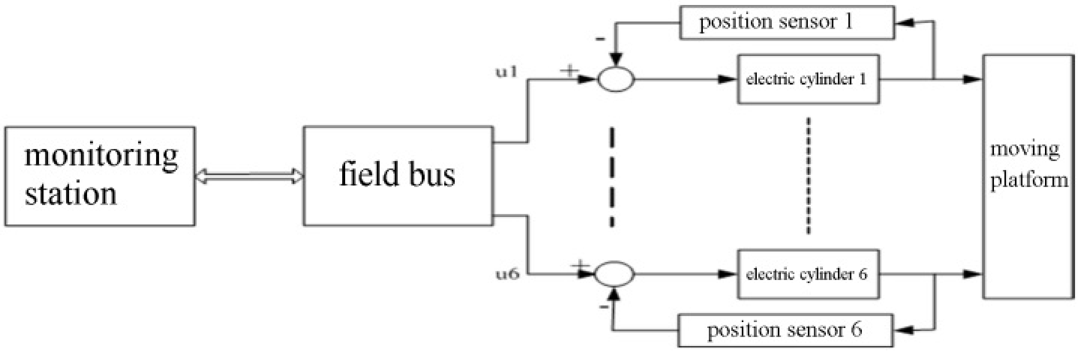

Figure 1. Control scheme based on the hinge space

This system uses the ideal of the distributed control architecture, making the whole system more modular structure, and more concise, which can make the six electric cylinder control down to its corresponding drive system more thorough, it is only necessary to solve the problem of the inverse kinematics of the moving platform by the monitoring station and the closed-loop control algorithm for each electric cylinder is completed by the drive system corresponding to each electric cylinder. The electric drive system of the electric cylinder uses a reasonable field bus to communicate with the monitoring station, and various sensors also feed the measured data via the field bus network to the monitoring station.

The idea of hierarchic design is applied to the prototype, and the whole system is divided into coordination layer and driver layer. As for the driver layer, the electric cylinder drive parts of the prototype are permanent magnet synchronous motors using self-developed dedicated servo drives with development fieldbus interfaces to achieve the driver servo. As for the coordination layer, this paper selects and uses industrial Ethernet communication to achieve the data communications between coordination layer and monitor workstation. An industrial Ethernet-CAN bus [6] gateway is designed as a carrier for the coordination layer, and in order to increase the reliability of the CAN bus by giving it a redundant design [7].

Averagely, the service time of the CAN bus is independent of time and satisfies the memoryless property of the exponential distribution, so the longevity of the CAN bus obeys the exponential distribution, suppose that the failure rates are λ_1 and λ_2, then the reliability is $R_1(t) = e^{\lambda_1 t}$ and $R_2(t) = e^{\lambda_2 t}$ respectively, and the probability function is as follows:

$$f_1(t) = \lambda_1 e^{\lambda_1 t} \tag{1}$$

$$f_2(t) = \lambda_2 e^{\lambda_2 t} \tag{2}$$

Due to full double redundancy and the two CAN channels are parallel relationships, the lifetime distribution density function of two CAN channel is:

$$f_s(t) = f_1(t) \times f_2(t) = \int_0^t \lambda_1 e^{-\lambda_1(t-x)} \lambda_2 e^{-\lambda_2 x} dx = \lambda_1 \lambda_2 \frac{e^{-\lambda_1} - e^{-\lambda_2}}{\lambda_1 - \lambda_2} \tag{3}$$

which gives the reliability of the module:

$$R_s(t) = \int_0^{+\infty} f_s(t)dt = \frac{\lambda_2}{\lambda_2 - \lambda_1} e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_2 - \lambda_1} e^{-\lambda_2 t} \tag{4}$$

If $\lambda_1 = \lambda_2 = \lambda$, then the life density function and reliability of the two degree CAN bus module are respectively:

$$f_s(t) = \int_0^t \lambda e^{-\lambda(t-x)} \lambda_2 e^{-\lambda x} dx = \lambda^2 t e^{-\lambda t} \tag{5}$$

$$R_s(t) = \int_0^{+\infty} f_s(t)dt = (1 + \lambda t)e^{-\lambda t} \tag{6}$$

Assuming that $\lambda = 2 \times 10^{-5}$, after the system works over 10000 hours, the single channel CAN bus reliability is $\exp(-2 \times 10^{-5} \times 10000) = 0.135$, while the double module reliability is Rs(10000) = 0.406, which indicates that the reliability of the use of the CAN bus is generally improved. As for the hardware of the driver layer, the coordination layer is the servo power cylinder drive and the industrial Ethernet-CAN bus network, respectively, which can be modular to implement the hardware design.

3. Driver Layer and Coordination Layer Software Design.

3.1. **Driver layer software design.** In this paper, software development is based on Code Composer Studio v3.3 integrated development environment developed by the Texas Instruments Corporation. The software is divided into modules based on the idea of modular programming.

- The main program is responsible for the initialization of TMS320F2812, including initializing the watchdog, locking rings, external clocks, GPIO, peripheral and external interruptions, the initialization of each variable.
- The motor rotor position reading subroutine is responsible for reading the results of the AD2S83 solution, and the rotor position is obtained by digital filtering.
- Because implementation method of the PID control algorithm is convenient, it is most commonly used in various control systems.

If the system's given value is $r(t)$, the actual output value is $y(t)$. The deviation value is $e(t) = r(t) - y(t)$. The control law of conventional PID controller is as follows:

$$u(t) = K_P \left[e(t) + \frac{1}{T_I} \int_0^t e(t)dt + T_D \frac{de(t)}{dt} \right] \tag{7}$$

In the digital control system, in order to process data and implement algorithms, the law of control needs to be discretized, and Equation (7) can be rewritten as:

$$\begin{aligned} u(k) &= K_P e(k) + K_I \sum_{j=0}^{k} e(j) + K_D \left[e(k) - e(k-1) \right] \\ &= K_P \left\{ e(k) + \frac{T}{T_I} \sum_{j=0}^{k} e(j) + \frac{T_D}{T} \left[e(k) - e(k-1) \right] \right\} \end{aligned} \tag{8}$$

The PID control algorithm in digital control system is implemented by software, which is flexible and can be easily improved according to the actual situation. When the system starts, ends or significantly increases the set value, the deviation will change in a short time which will inevitably cause the integral accumulation of PID arithmetic that can calculate the control quantity is too big resulting in larger overshoot, and even leads to the oscillation of system which is not allowed in some control process. An integral separation PID control algorithm is adopted by the closed-loop control algorithm, which has improved the control performance by maintaining the integral and reduce the oversize. The concrete implementation is as follows.

a) According to the actual situation of the control system, error limit is set as ε.

b) When $|e(k)| > \varepsilon$, remove the integral effect, use the PD control, so, the over-correction can be avoided and the system has a faster response, and PD control algorithm is as follows:

$$u(k) = K_P e(k) + K_D \left[e(k) - e(k-1) \right] \tag{9}$$

c) When $|e(k)| < \varepsilon$, putting into the integral effect, and using the PID control can guarantee the control accuracy of the system. The PID control algorithm is as follows:

$$u(k) = K_P e(k) + K_I \sum_{j=0}^{k} e(j) + K_D \left[e(k) - e(k-1) \right] \tag{10}$$

In Equations (7)-(10):

u_k – The computer output value at the kth sampling time
e_k – The input deviation value at the kth sampling time
e_{k-1} – The input deviation value at the $(k-1)$th sampling time
K_P – Scale factor
K_I – Integral coefficient
K_D – Differential coefficient

- The SVPWM subroutine is responsible for the Clarke transformation, Park transformation, Park inversion, and Clarke inverse. And the voltage space vector SVPWM control drives the AC permanent magnet synchronous motor.
- The A/D interrupt service program is responsible for reading the transformation of A/D converters allowing the A/D transformation to synchronize with PWM in software design, which is the PWM triggering A/D conversion.
- The full comparator overflow interrupt subroutine is responsible for updating the values of the respective registers and driving the motors according to the calculation result of the closed loop algorithm.
- The CAN interrupt service program is responsible for: first, receive the various instructions and commands that are passed down from the monitoring station; second, the displacement, speed and temperature of the electric cylinder are passed to the monitoring station.

3.2. **Coordination layer software design.** The coordination layer software design is software design for the Ethernet-CAN bus gateway. The Ethernet connection is done by the MIPS core microprocessor PIC32MX795F512L and DP83848, while CAN communicate PIC32MX795F512L and CTM8251DI. The following are described respectively:

- The software development environment uses the MPLABIDE software development environment.
- This paper uses the open source real-time embedded operating system – μC/OS-II. μC/OS-II is a complete, portable, curable, retractable, preemptive multi-task kernel [8]. The migration of μC/OS-II on PIC32MX795F512L mainly completes the OS_CPU.H, OS_CPU_A.S and OS_CPU_C.C [9,10].
- The layered model of the TCP/IP protocol stack [11-13], typically consists of four layers: the link layer; the network layer; the transport layer; and the application layer. The embedded TCP/IP protocol stack [12] is used here.

4. **Experiment and Analysis on the Control System Prototype.** The experiment platform is shown in Figure 2.

Figure 2. Experiment platform

4.1. **Initialization of system and the motor cylinder.** This experiment makes use of the monitoring software in workstation to send and receive control command, which mainly includes driver layer: self-check; system initialization; main power switch; motor cylinder reset.

After execution of above commands, motor cylinder can download and receive the position command from monitoring software and start the close-loop servo control for motor cylinder position. As illustrated in Figure 3, after execution of above commands, corresponding indicator light will light up meaning the servo driver has executed the command successfully.

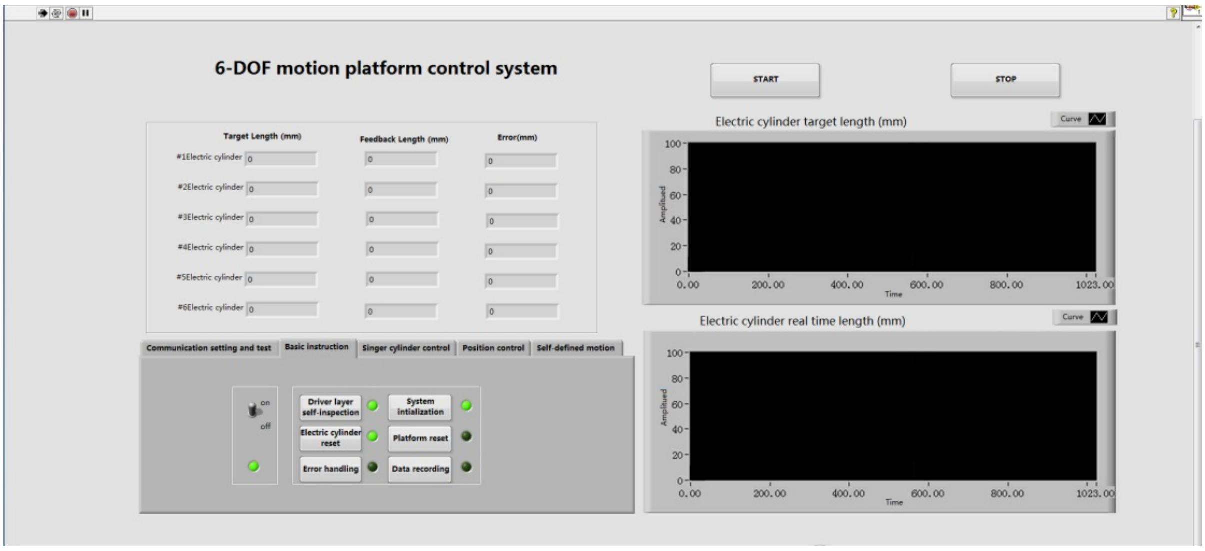

Figure 3. System and electric cylinder initialization results

4.2. **Close-loop control test for motor cylinder position.** In this experiment, the full-stroke of the experiment is 100mm, hence assuming the experimental travel to 80mm. According to preliminary test results, the PID parameters of this test are set as follows: the monitoring software will send position command to servo driver per 20ms with the target displacement of 80mm, execution time of 10s, proportionality coefficient of 13.4, integral coefficient of 0.8, and differential coefficient of 0.5. After receiving the positioning command, servo driver will upload current displacement value in a meanwhile, which will be shown in the waveform of target and actual displacement values. As illustrated in Figure 4, we can observe that the actual displacement feedback from the servo driver is broadly consistent with the target displacement. Therefore, we can conclude that the close-loop control for motor cylinder positioning is performing very well.

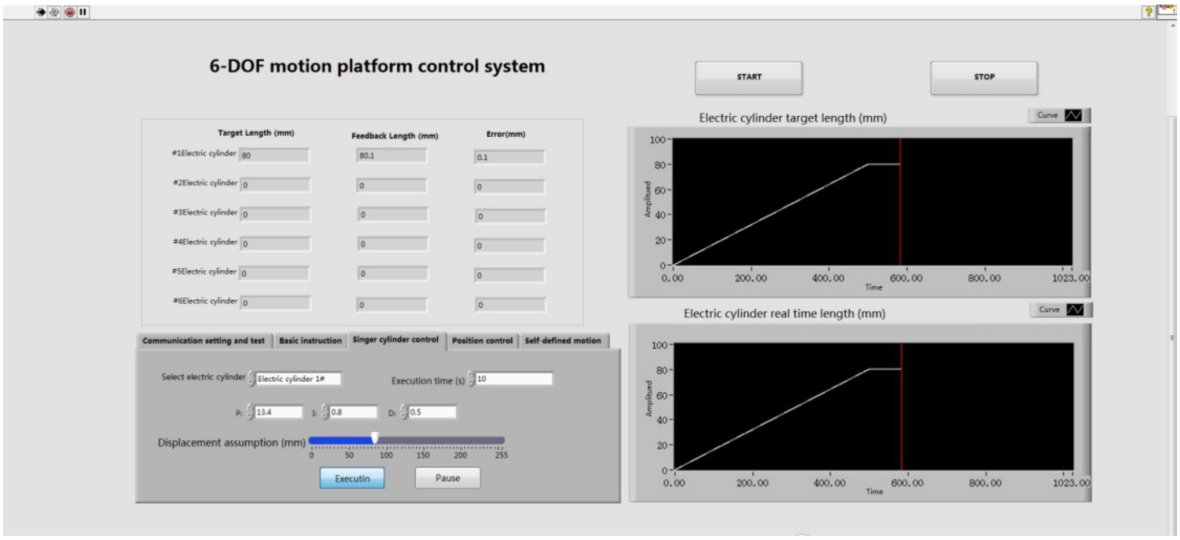

FIGURE 4. Single-cylinder position closed-loop effect

4.3. **Servo driver and Ethernet – CAN gateway communication test.** In this experiment, we will test the functionality of CAN communication between driver layer and coordination layer. Coordination layer will continuously send 8-byte data to the driver layer of servo driver. After receiving the data, driver layer will send it back and use YOKOGAWA logic analyzer to capture the CAN message from bus. Details are as follows.

a) Properly network the servo driver of driver layer, coordination layer and YOKAGAWA logic analyzer. The servo driver and coordination layer should have downloaded the CAN communication program. The driver layer test program will send back the data after receiving the CAN message.

b) With the use of YOKAGAWA logic analyzer, we can capture waveform from CAN bus and analyze it. In the program, we set CAN Baud rate as 500kBps, CAN message identifier as 001, experiment data as 00-07. The captured waveform from CAN bus is illustrated in Figure 5. After the CAN message has been captured, the program will execute CAN message analyzing function. According to the results, we can observe that captured CAN message is the same as what we have expected.

5. **Conclusions.** This paper designs a high-precision and high-reliability 6-DOFs motion platform. The ideal of layered design is applied to the prototype, and the whole system is divided into coordination layer and driver layer. In order to improve the reliability and control performance of the system, a comprehensive double redundant design is adopted and an integral separation PID control algorithm is designed. The experimental results show that the close-loop control for motor cylinder positioning is performing very well and the coordination layer and the driver layer CAN communication module are successfully debugged. The results verify that the control system meets the requirements.

There are still some research topics that will be studied in the future. Details are as follows: we can try to use other reliable commercial operating systems; intelligent control technologies such as neural network control technology and fuzzy control technology yet to

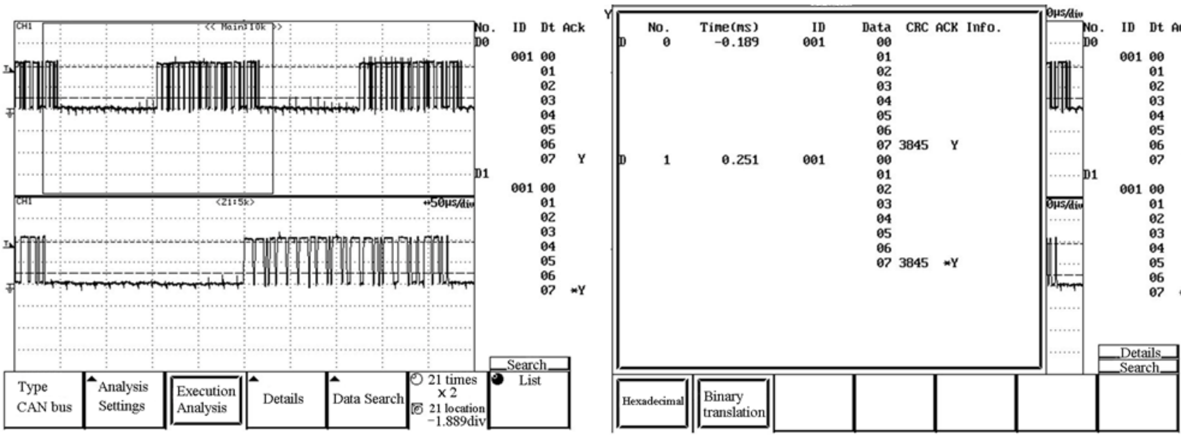

FIGURE 5. Data of CAN message waveform captured by DL1640L and packet analysis result

be studied; the follow-up studies require a lot of system testing, including: control system error analysis, PID parameters in-depth optimization and prototype reliability testing.

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