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THE APPLICATIONS OF XY STAGE CONTOUR TRACKING CONTROL

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Abstract. *A PC-based two-axis XY control system is developed in this research. The MATLAB/Simulink tool is used to execute the motion control methodology. The time domain system identification method is applied to obtaining the X-axis and Y-axis system models, respectively. The Ziegler-Nichols rule is applied to designing the PID controller parameters, and the controller is developed with motion control card in actual platform. Two trajectories, i.e., square, and circle contours, are conducted successfully. We propose our method that provides the better performances on average tracking error and standard deviation for different contour tracking.*

Keywords: XY platform, Trajectory control, System identification, PID controller design

1. **Introduction.** In the two-axis motion trajectory design, the controller design and development are an important issue to discuss. The system is widely used in many areas, such as work feeder of CNC lathe, CNC milling/drill press machines, and the work table of laser cutting applications. For the motion control, it is not only in the control of the movement but also needs to consider the speed, acceleration, deceleration into the design of the system box. The XY stage is composed of X-axis and Y-axis motion mechanisms and each motion axis is driven by individual actuator. The key of the motion control is to design the servo controller, and the others are the mechanical structure and accuracy of command path. We develop the voltage control method that voltage command sends to the motor driver to achieve the better performances of trajectory control.

PID control is the most common control law for position control or speed control. There are many methods to determine the parameters. Ziegler-Nichols rule is the most common [1]. To use the method as the input step signal, we can learn from the output response control performance and do the adjustment. Although PI and PID controller architecture is simple, it is difficult that we want to accurately reach the location quickly and no overshoot, and the parameters need to plan [2-4]. Traditionally, the programmable logic controller (PLC) has been used in the industry because its system architecture is simple and reliable. However, in recent years, computer functions become more powerful, and the execution trajectory becomes more complicated. The traditional PLC architecture does not meet the demand and is replaced by PC-base [6]. Many experts have used PC-based architectures to implement the platform trajectory control [5-10].

This paper mainly uses PC-based architecture as the main method to control, and uses MATLAB-Simulink. The system identification should be solved for each axis model, and the PID parameters are obtained through Ziegler-Nichols rule. In this study, we use two motion control cards. One motion control card is to output analog voltage command (digital-to-analog converters, DAC) and read signal by sensor (analog-to-digital converters, ADC). The other card is used to read the position signal from the linear scale. We integrate the closed-loop architecture by two motion control cards, and the trajectory control design is using a voltage command to the servo drive to actuate the XY platform.

The remainder of this paper is organized as follows. Section 2 describes the system architecture. In Section 3, PID controller and Ziegler-Nichols rule are described. The experimental results are shown in Section 4. Section 5 concludes this paper.

2. **System Architecture.** Permanent magnet synchronous motor (PMSM) is a permanent magnet for the rotor to replace the traditional wound-rotor motor. PMSM generates the wave of back-emf which is more suitable for the rotating magnetic field. PMSM has wide magnetic flux, high power, high moment of inertia, etc. Compared to the induction motor, the rotor as a magnetic material inertia is low. In the same load, the speed of response is fast because the PMSM does not need excitation current; therefore, it has high efficiency and does not have problem of high temperature. In the industry, the PMSM is widely used in servo control systems of high-performance. The mathematical models of the PMSM are shown as:

$$v_q = Ri_q + \frac{d\lambda_q}{dt} + \omega_s \lambda_d \tag{1}$$

$$v_d = Ri_d + \frac{d\lambda_d}{dt} - \omega_s \lambda_q \tag{2}$$

with $\lambda_q = L_q i_q$, $\lambda_d = L_d i_d + L_{md} I_{fd}$, $\omega_s = P\omega_r/2$, where P is the pole pairs, v_d is the direct-axis voltage, v_q is the quadrature-axis voltage, i_d is the direct-axis electric current, i_q is the quadrature-axis electric current, L_d is the direct-axis inductor, L_q is the quadrature-axis inductor, λ_d is the direct-axis magnetic flux, λ_q is the quadrature-axis magnetic flux, R is the stator resistance, ω_s is the inverter of switch frequency, ω_r is the speed of rotor, L_{md} is the direct-axis mutual inductance, and I_{fd} is the equivalent direct-axis electric current. The electric torque is given as:

$$T_e = 3P[L_{md} I_{fd} i_q + (L_d - L_q) i_d i_q]/2 \tag{3}$$

The motor dynamic equation is expressed as:

$$T_e = T_L + B\omega_r + J\dot{\omega}_r \tag{4}$$

where T_L is the load torque, B is the damping coefficient, and J is the rotational inertia. According to the reference, the step response of rotor position is based on the mechanical parameter technique. The parameters of XY biaxial PMSM moving platform are as follows: J is rotational inertia, and B is the damping coefficient. In Figure 1, suppose the location command d_{mi} is step function, the position controller is proportional function, and the closed loop transfer function is

$$\frac{d_i(s)}{d_{mi}(s)} = \frac{\frac{K_t}{J}}{s^2 + \frac{B}{J}s + \frac{K_t}{J}} \tag{5}$$

where K_t is the gain of parameter. Suppose the system is the second order transfer function (Figure 1(b))

$$G(s) = \frac{Y(s)}{E(s)} = \frac{\omega_n^2}{s\,(s + 2\xi\omega_n)} \tag{6}$$

Suppose $G(s)$ is the system state, the relationship between output and input is:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{7}$$

After using the inverse of Laplace transform, the output of t-domain equation $y(t)$ is

$$y(t) = 1 - \frac{e^{-\xi\omega_n t}}{\sqrt{1-\xi^2}} \sin\left(\omega_n \sqrt{1-\xi^2}\, t + \cos^{-1}\xi\right) \quad t \geq 0 \tag{8}$$

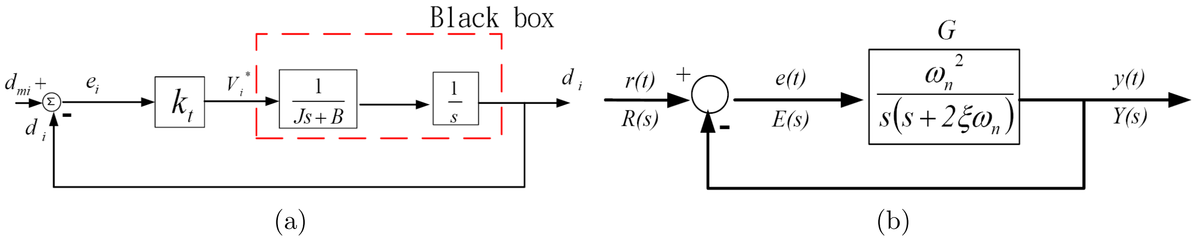


Figure 1. (a) The equivalent system model; (b) the second-order mathematical model

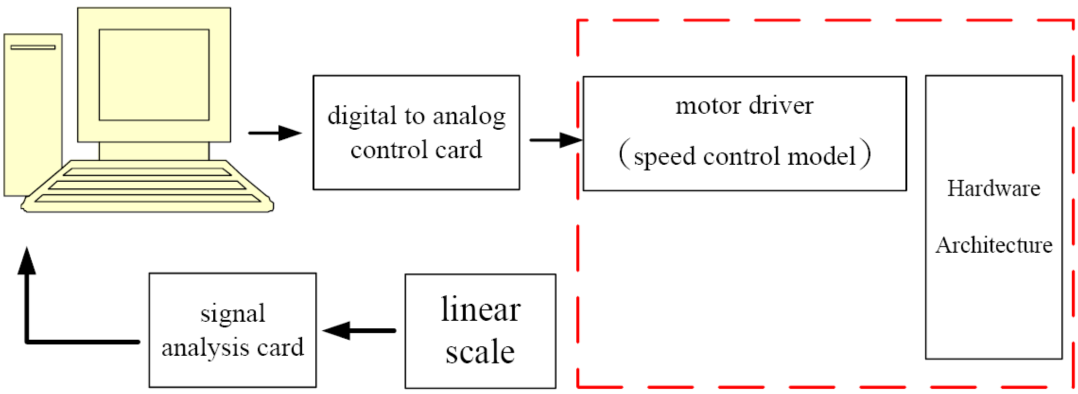


Figure 2. Actual system simulation

As mentioned previously, the establishment of the system dynamic model is an important step before designing the control system, but the system includes the signal from the motion control card which starts through the servo drive, AC servo motor, the platform and the ball screw. Although there are a few parameters provided from the manufacturers or indirectly derived, some parameters can be obtained by some equipment, and some mathematical models of the motor have the explanation in many textbooks. Most of the parameters are unknown like driver because the functionality is powerful and the internal electronic circuit is quite complex. The driver is like another controller. Ball screws and other mechanical equipment in the hardware equipment should consider like friction force. This paper mainly tests in the t-domain.

In this experiment, the unknown subsystem is regarded as an unknown black box (Figure 2). The black box mode is used to establish the mathematical model in the unknown system, and the dynamic mathematical model is used to design the control system. The variation of system output is observed by adjusting the value of the system gain value (K_t). By classical control theory, the system will get different damping constant (ξ) and the oscillation frequency (ω_n), and brings the two parameters into the standard second order transfer function to obtain the predicted system mathematics model. We can know when the gain decreases, the damping value will gradually increase, and the response will inversely proportionally increase.

Because the K_t value can be used to obtain different responses, damping constants and oscillation frequencies in the former method, the results have different advantages and disadvantages. However, this study is based on the system which can perform trajectory stably so we choose the critical damping to do the design. Using the MATLAB-Simulink software output command can get the output position by the linear scale. After repeating the experiments, we can achieve the response in critical damping ($\xi = 1$).

To obtain natural damping frequency (ω_n), we redefine the rise time (t_r) for final value of step response from 0 percent to 90 percent. The related formula between the rise time

t_r and natural damping frequency ω_n is:

$$t_r = \frac{3.88959}{\omega_n} \tag{9}$$

From the above formula, we obtain the natural damping frequency ω_n of each moving axis and the original damping $\xi = 1$. The above two parameters are brought into the standard second-order equation and we can obtain:

X-axis system equation is:

$$\frac{1.034}{s^2 + 2.03377s + 1.034} \tag{10}$$

Y-axis system equation is:

$$\frac{1.047708474}{s^2 + 2.04715s + 1.04770874} \tag{11}$$

3. PID Controller Design.

PID controller is popular because the principle is very easy and the electric circuit can be implemented easily. Adaptability and toughness are not too bad to be used in a variety of industry. It can be seen from Figure 3 that the system is closed loop control architecture. The traditional control PID transfer function is:

$$G_c(s) = K_P + \frac{K_I}{s} + K_D s = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{12}$$

with $K_I = K_P/T_I$, $K_D = K_P T_D$, where K_P is the proportional gain, T_I is the reset time, and T_D is the derivative time.

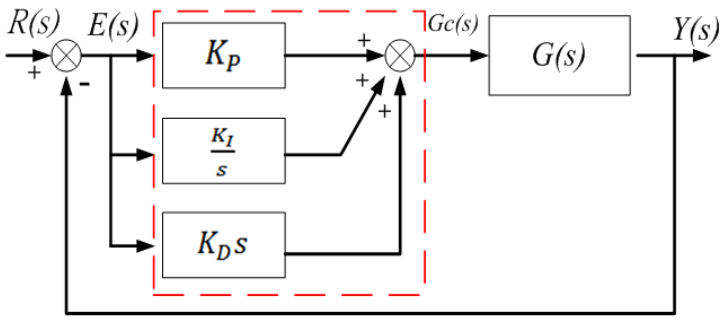


FIGURE 3. PID control block diagram

The earliest PID control theory was written in 1922 by Minorsky's thesis, but until 1942 Ziegler and Nichols together proposed the well-defined gain adjustment method for PID control theory [1]. After continuous experiments and analysis, they finally summed up an ideal formula [10], and it improved the development of the later control industry. Until today, this formula and the improved version are still used in a variety of closed loop system. Servo motor is the most commonly used for position and speed control. We use the closed loop to find parameters. The adjustment method is to set the integral and differential gain to zero first, and gradually increases the proportional gain from zero until the limit gain (K_U). The controller output oscillates at a constant value. K_U and the oscillation period (T_U) are based on different types, and we follow the table to set proportional, integral and differential gain. The parameters K_U, T_U are brought in the table, and we can obtain the PID parameters.

Table 1. Z-N parameter correspondence table

Ziegler-Nichols method			
Controller type	K_P	K_I	K_D
PID method	$0.6K_U$	$\frac{2K_P}{T_U}$	$\frac{T_U K_P}{8}$

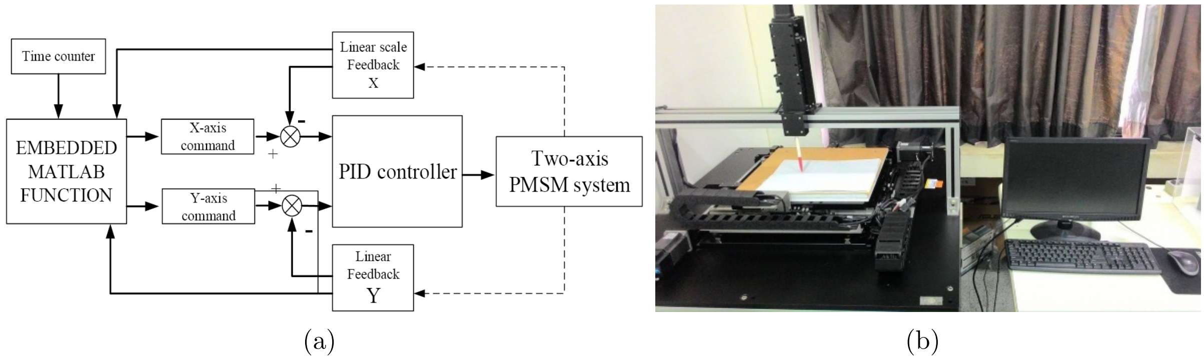


Figure 4. (a) Control system block diagram; (b) experimental control stage system

4. **Experimental Results.** This section describes the results that method is used to perform trajectory control in this research. Figure 4 shows the flow chart of the program execution in MATLAB and the architecture diagram using the Simulink block diagram. This study mainly focuses on the program written in the embedded MATLAB function box to perform various track action commands. By using the time counter, the system can judge time with each segmented trajectory whether pointing that we expect. Compared with the feedback value from position command and sensor, the PID controller outputs the next command finally.

The Ziegler-Nichols parameter adjustment rule [10] is described in Section 3. Substituting the parameters in table can infer the estimated value of the corresponding PID parameter. The PID parameters in the later trajectory movement will depend on the closed loop method. The following are the parameters.

X-axis parameters: The experiments show that the gain value K_t reaches 1/32, the system will reach the critical stability. It can be found that adding the gain will let the system reach the critical steady state, and the oscillation period is 14(s). Two parameters $K_U = 1/32$ and $T_U = 14$(s) are brought into the Ziegler-Nichols rule table, and then we can get the following parameters:

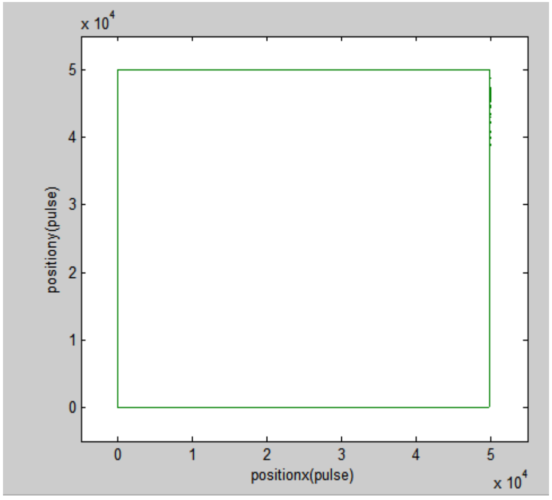
$$K_P = 0.6K_U = 0.01875, \quad K_I = \frac{2K_P}{T_U} = 0.00267857, \quad K_D = \frac{K_P K_U}{8} = 0.0328125$$

Y-axis parameters: Using the same method can obtain the critical stability when the K_t reaches 1/42, and the oscillation period is 14(s), the following are the parameters:

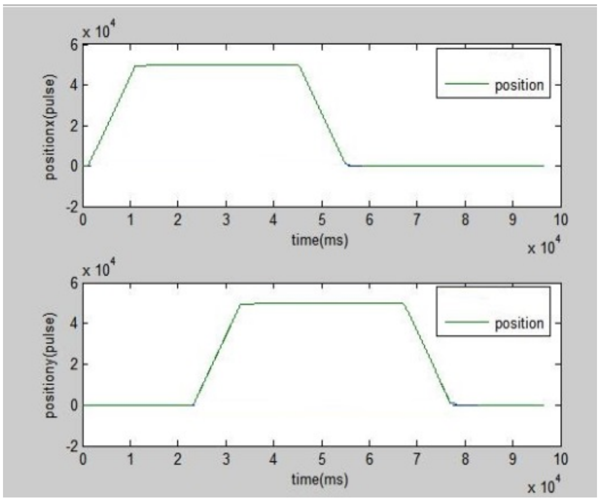
$$K_U = 1/42, \quad T_U = 14, \quad K_P = 0.6, \quad K_U = 0.0142857,$$

$$K_I = \frac{2K_P}{T_U} = 0.0020408, \quad K_D = \frac{K_P K_U}{8} = 0.025$$

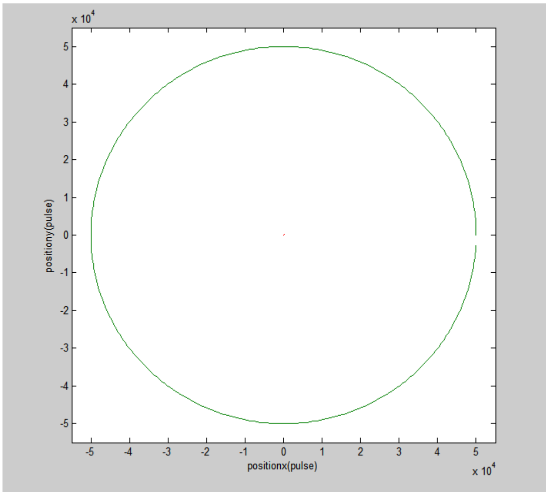
The above PID parameters are brought into the controller, and the actual platform accesses the feedback data by the linear scale in MATLAB. The use of XY axis to do the trajectory movement can achieve the following results. Figure 5 shows the trajectory tracking performances of the proposed PID controller for the square contour and circle contour. The control objective is to maintain the system states in tracking the reference



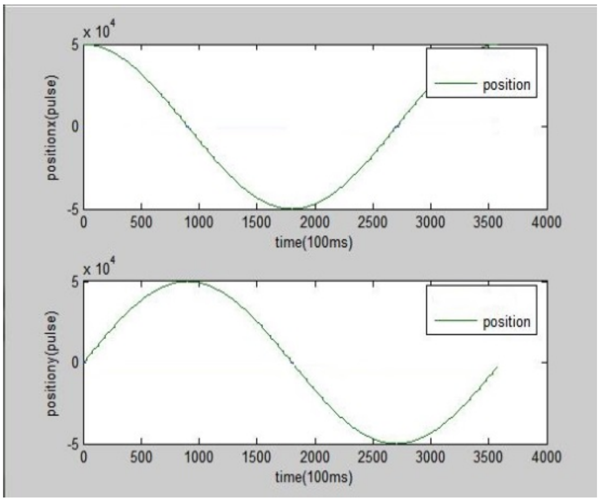
(a)



(b)



(c)



(d)

FIGURE 5. Experimental results of trajectory: (a) square trajectory; (b) X-axis and Y-axis position tracking response; (c) circle trajectory; (d) X-axis and Y-axis position tracking response

TABLE 2. The experimental results of trajectory tracking error

	Square contour	Circle contour
Average tracking error (μm)	283.485	721.348
Tracking error standard deviation (μm)	236.02	328.24

square input contour. Figures 5(a) to 5(d) illustrate the tracking responses of the position displacement, and motion trajectory.

The position data can be accessed by the linear scale, and Table 2 lists the tracking error values of our proposed method including the performance measures of the average tracking error and the standard deviation of the tracking error for the square and circle contours.

5. **Conclusions.** The main purpose of this paper is to design the PID controller for XY trajectory control. The MATLAB tool is employed to design the simulation algorithm and it can be achieved on the actual hardware test. The PID method based on the Ziegler-Nichols method is developed to control the two-axis permanent magnet synchronous motor in the XY platform to perform motion control. The experimental results show that

our proposed method can achieve better performance in circle and square trajectories control. It can be developed and implemented to be a useful PID controller for industry applications in the future.

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