Design of rolling ball control system based on OpenMV

Linjie Zhou¹, Enyi Xu, Donghong Chen, Chenghao Xu, Xiai Chen, Suan Xu and Ling Wang

College of Mechanical and Electrical Engineering, China Jiliang University, Hangzhou 310052, China

¹E-mail: 1600103109@cjlu.edu.cn

Abstract. The ball-on-plate system, a non-linear control system with a 2-degree of freedom, is crucial for understanding the control system applications. As increase of the non-linearity with the degree of freedoms, the system can be used to test and identify different aspects of controls. This paper describes the design and implementation of a ball-on-plate system based on OpenMV that includes machine vision modules. Camera OV7725 with chip model of STM32F765 in OpenMV detects and calculates ball position on the plate in real time, and then the OpenMV sends the position data of the ball to the main Micro Controller Unit through a serial port. The MCU calculates the data with a cascade PID controller, and outputs the PWM wave to control the rotation angle of the steering engine. The steering engine drives two vertical parallelogram linkage mechanisms to manipulate the motion of the plate. Thus, the system can exactly control the motion state and position of the ball on the plate in real time.

1. Introduction
In recent years, the explosion of artificial intelligence indicates that automation will enter a more active era. An existing control system, including automatic control theory and process control theory, is based on a common point that the controller is based on a precise linear mathematical model [1, 2]. However, for most systems, there are nonlinear, time-varying and hysteresis, and it is difficult to set up the PID model pertinently [3, 4]. The ball rolling control system is an image model. The ball control system is a multi-variable, double-input two-output two-degree-of-freedom nonlinear system, the mathematical model of the system is not easy to establish, and the ball rolling control system device is shown in Figure 1. The ball rolls freely on the board, uses the camera to collect the ball's position, converts the analog signal to the digital signal to the PID controller [5-7]. This paper presents a rolling ball control system controlled by classical regulation principle. The system consists of MCU, camera and sensor module. It has the characteristics of high feasibility, wide application and classic control difficulty.

2. System structure design
The whole system consists of support base, camera fixed rod, motor drive and actuator and plate. Actuators on the single shaft of the motor and tablet by two connecting rod and a revolving arm, two connecting rod length equal, turn the arm length and fixed on two universal joint on the surface of the plate under equidistant, and jib rotating center as the rotation center of the plate in the same vertical, to form a parallelogram structure, makes the steering gear rotating angle and the angle of the plate in the axial plane approximately equal to its system structure response linearity is good, good for automatic control [8]. The system structure design is shown in Figure 1.
3. **System theory analysis and calculation**

m is the mass of the ball, r is the radius of the ball, x and y are the displacement of ball x and y direction, \( \theta_x \) and \( \theta_y \) is the inclination of the plate x and y direction, \( \tau_x \) and \( \tau_y \) are external torques for plate x and y direction, L is the length of connecting rod mechanism, J is the moment of inertia of the ball, \( J_P \) is the moment of inertia of the plate. The calculation formula of the system is as follows:

\[
(m + J/R^2)x + mgsin\theta_x - mx\theta_x^2 - my\theta_x\theta_y = 0. \tag{1}
\]

\[
(m + J/R^2)y + mgsin\theta_y - my\theta_y^2 - mx\theta_x\theta_y = 0. \tag{2}
\]

\[
\tau_x = (JP + J + mx^2)\theta_x + 2mx2\theta_x + 3mxy\theta_y + mgxcos\theta_x. \tag{3}
\]

\[
\tau_y = (JP + J + my^2)\theta_y + 2my2\theta_y + 3mxy\theta_x + mgycos\theta_y. \tag{4}
\]

(1) The first and the second formula are mechanical equilibrium equations. The third and the fourth formula are moment balance equations. We choose a ball with a mass of 10g and a radius of 2.5cm. The selection density is 1.18g/cm³, the size is 55cm*55cm, the thickness is 4mm, and the quality is 1.4278Kg of acrylic sheet. In order to speed up the adjustment speed of ball system, we choose \( |\theta_x| < 12^\circ, |\theta_y| < 12^\circ \) range of redundancy according to the calculation.

(2) The mechanical analysis diagram is shown in Figure 2. The X-axis steering gear and the Y-axis steering gear will be connected to the axis and the other side perpendicular, and in the x and y direction, they will be combined with two connecting rod bodies to form a standard parallelogram structure. Such mechanical structure can ensure that the lifting angle of the X-axis steering gear is the tilt angle of the plate in the X-axis direction, so that the system has a better linear relationship in the PID adjustment process.

(3) After system structure analysis, the cricket system is a nonlinear control system. Referring to the book Process Control Engineering, the cascade control system forms two closed loops, which are a fixed value control system for the main circuit and a follower system for the secondary circuit [9]. Referring to a simulation study of a three-degree-of-freedom cascade control computer simulation, it is true that the secondary loop of the cascade control system can overcome the nonlinear constraint to a certain extent. Finally, we chose the cascade control system [10]. In order to verify the simulation results, we made a comparative analysis of the results in the first follow-up experiment.
Figure 2. The mechanical analysis diagram (take the X-axis as an example).

4. Hardware and software design
The rolling ball control system is divided into camera acquisition module and the main MCU module. The camera acquisition module can calculate the position coordinates and the velocity of the ball in the camera image. The camera acquisition module sends these data through serial port to the main MCU module. The main MCU module use the data received by the serial port to control the angle of the two dimensional plane of the steering gear. The main control module completes the man-machine interaction through the LCD touch screen. The specific hardware block diagram is shown in Figure 3.

Figure 3. Hardware block diagram of the rolling ball control system.

In order to achieve the ideal control effect in a short time, the system uses the cascade PID controller, camera module feedback ball relative coordinates, the coordinates of time differential that the rate of movement of the ball. By controlling the attitude of the steering gear control plate, the ball can get the proper acceleration, thus controlling the relative position of the ball. The outer ring on a single axis to realize position control of the ball, the ball the current input variables, output for the expectation of ball speed, closed in ball speed control, the input for the ball in unit time position variation, output for the duty ratio, namely the rotation angle of steering gear. The software flow chart is shown in Figure 4.
Figure 4. Software block diagram of the rolling ball control system.

5. Experiment and analysis

We used a cascade PID controller to optimize the internal and external loops to a 4:1 beat ratio, adding integral limit and deadband control. The result is relatively good steady state performance and dynamic performance. In order to test the final performance of the system, we used the following 9 areas of the schematic diagram of Figure 5 to demonstrate that each area has a diameter of 20 mm and a small ball diameter of 15 mm. We allow an error of ±5 mm. Figures 6 and 7 show our image processing effects, and we mark the center of the target with a cross [11-12].

Figure 5. Nine regional maps. Figure 6. The mark. Figure 7. The mark in the corner.

We designed the foundation and played two parts to measure and analyze the system. In the basic part we propose four topics to complete and record the time as shown in Table 1.

In the play part, we use a laser pen to let the ball track to monitor his real-time performance. We can basically stabilize in the area of ±10 mm of the target point. The response is more sensitive and can be measured with a 150 mm step response test and a follow-up test with a speed of 30 mm/s. Figures 8 and 9 show that our system tracks targets in real time.

Figure 8. The location before tracking. Figure 9. The location after tracking.
Table 1. Completion and time recording.

| Trials | Place the ball in area 2, and control to keep the ball in the area for no less than 5 seconds. | Control the ball to enter zone 5 from zone 1 and stay in zone 5 for no less than 2 seconds (s) | The control ball starts from area 1 and enters area 2, area 6, stops at area 9, and stays in each area for at least 2 seconds (s) | The ball starts from zone 4 and acts as a wrap around zone 5 (not entering). After 3 weeks of exercise, it stops at zone 9 and remains no less than 2 seconds (s) |
|--------|------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| First  | completed                                                                                | 1.9/1.3                                                                           | 12.6                                                                              | 16.2                                                                               |
| Second | completed                                                                                | 2.5/1.4                                                                           | 13.6                                                                              | 16.8                                                                               |
| Third  | completed                                                                                | 3/1.4                                                                             | 12.3                                                                              | 15.2                                                                               |
| Fourth | completed                                                                                | 2.5/1.1                                                                           | 12.7                                                                              | 15.8                                                                               |
| Average| completed                                                                                | 2.8/1.3                                                                           | 12.8                                                                              | 16.0                                                                               |

6. Conclusions
As a typical multivariable and nonlinear control object, the rolling ball control system is of great significance for the research of control methods of the modern, the experiment was carried out on the system, we have been able to complete the fixed-point stability, on the plate rolling, according to a graphics path from any starting point to another target points and can stop to remain at rest, and other functions. The classical control method adopted in this paper can also be used for fuzzy control. The limitation of PID is that it relies too much on the mathematical model of the system, and there is a certain lag in control. We will use fuzzy control to continue to improve the system. The research of rolling ball control system has greatly promoted the theory of automatic control and the theory of process control. The application of the camera and the solution of the lens visual distortion have also taken a step closer to the field of artificial intelligence.

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