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PID TRAJECTORY TRACKING CONTROL FOR BALL-AND-PLATE SYSTEM

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ABSTRACT: Ball-on-Plate (BoP) is developing a ball-and-beam system. This transformation transforms a single input-multi output (SIMO) system into a multi input-multi output (MIMO) under-actuated system. In this paper, we utilize the PID method—a popular linear control method in industry and academia—to track trajectory control for BoP. This system's self-made hardware is presented to test PID control through an experiment. This method is shown to track trajectory control well for real-time BoP.

KEY WORDS: Ball-on-Plate; PID Control; MIMO under-actuated system; linear control.

1. INTRODUCTION

BoP is an extension of the Ball-Beam system [1], which has two degrees of freedom. Due to its non-linear characteristics, it has generated interest in studying and analyzing classic, modern, and non-linear controllers. The system is volatile, as slight plate inclinations in an open loop can cause indefinite displacement of the ball. In [2], the model of this system is presented in the form of transfer functions. Therefore, the pole-placement method stabilizes this system on simulation at an equilibrium point. However, a non-linear model is more complicated than a linear system. Thence, the result of that research is only successfully described in simulation. PID control [3] is admitted as a simple, effective control method. It is shown to be effective in controlling single input-single output (SISO) systems, such as DC motors [4] or magnetic levitation systems [5]. However, for the MIMO under-actuated system, the SISO structure of the PID algorithm makes it difficult to apply for these models. PID blocks are arranged to adapt to these models, such as controllers for tower cranes [6]. In [6], An ANFIS-fuzzy controller is created from the original PID controller. PID control can be applied directly to an accurate model without simulation due to its experimental calibration features.

In [7], a table of phototransistor structures on the plate detects the ball's position. However, a camera/ webcam can be regarded as a general sensor for many projects. Therefore, using the camera to replace the structure of the phototransistor is a solution that has a brighter future [8]. PID control for BoP when the camera is used as a sensor provides a solid foundation for future research on MIMO under-actuated systems. In [9], only PID control is used for balancing at the equilibrium point. A solution for trajectory control for this model has not yet been presented. In [10], sliding control is presented. However, the sliding control method requires exact dynamic equations and system parameters. This requirement is impossible for most systems in real life.

This paper presents a PID structure that can control accurate BoP trajectories. Trajectories are round and square signals. The sensor, in this case, is a camera.

2. BALL AND PLATE MODEL

The model of BoP is shown in **Error! Reference source not found.**. The Block diagram of BoP is shown in Fig. 1 and 2. This system uses PID controllers to manage the ball's position on the plate. Since there are two variables to control, this system requires two PID controllers. First, the PID controller manages the position along the X-axis. The second PID controller manages the position along the Y-axis.

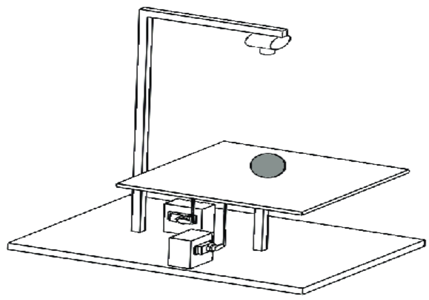

Fig. 1. Structure of BoP

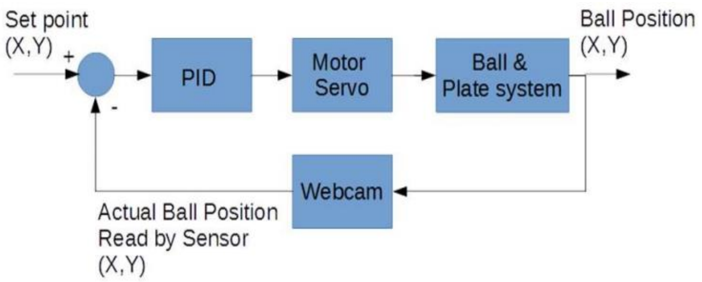

Fig. 2. Block Diagram of BoP Control System

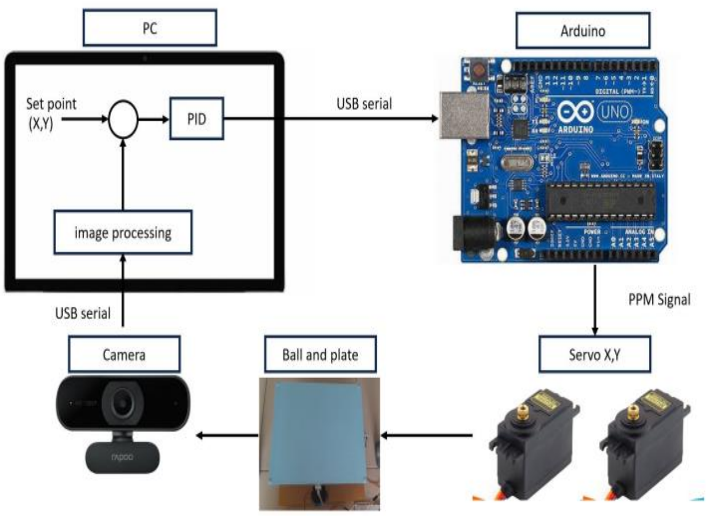

Fig. 3. The hardware structure of the system

In Fig. 3, the system consists of three primary devices. The first device is a PC. This PC performs multiple tasks, such as setting the control interface's set point, computing position errors, running the PID controller, and sending serial data output to Arduino. The second device is Arduino. Arduino receives serial data from the PC to adjust the angles of two servo motors. The last devices are a webcam and a ball position sensor.

Fig.4 shows the control interface. The interface allows users to select the system's balance and tracking modes, such as balancing at the centre of the plate, balancing at four corners, or moving the ball in a circular or infinity pattern.

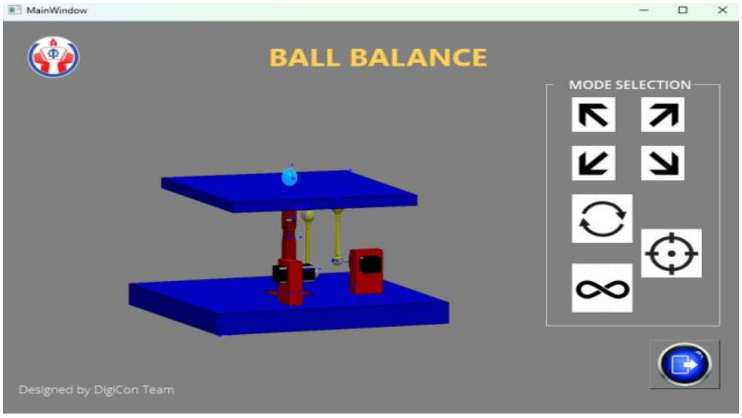

Fig. 4. Control interface on PC

3. CONTROL METHOD

The parameters of the PID controller are determined by trial and error. First, we focus on proportional gain, which must be large enough to allow the ball to move freely on the plate. However, if the proportional gain is too high, it will cause significant fluctuations, making it difficult for the response to reach a steady state.

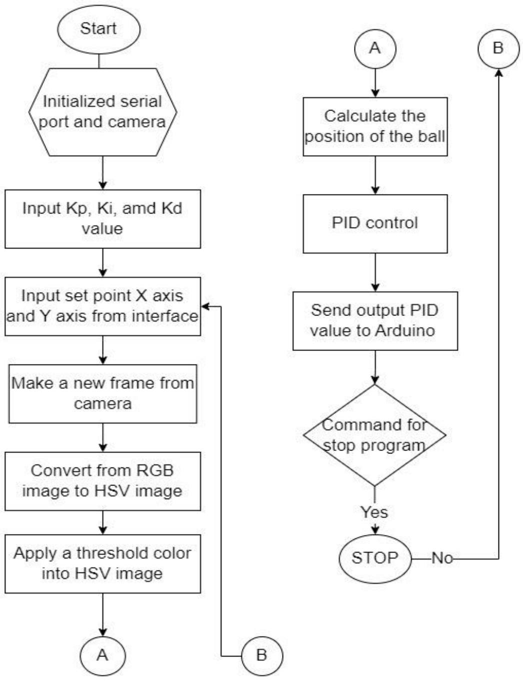

Fig. 5. Operation flow chart

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Next, we add derivative gain to reduce these fluctuations. The ratio between proportional gain and derivative gain is about eight to ten times. Finally, we add a small integral gain to minimize steady-state error. We prevent integral terms from accumulating above or below pre-determined bounds.

Fig. 5 explains how the camera detects and tracks the ball. From Fig. 5, the ball was detected based on its colour. Images captured by the camera are first converted into HSV format. A threshold value creates a black-and-white image from the HSV image. This process turns the ball's colour white and the plate's black. PC processes this image, identifying the ball as white. Using this white colour, the PC calculates the ball's coordinates. These coordinates are determined using a PID controller. Output values from PID calculation are then sent to Arduino via serial communication.

4. EXPERIMENTAL RESULTS

The graphs below illustrate BoP's tracking performance as it controls the ball to reach the desired positions X_set and Y_set. Blue and orange lines represent the set values X_set and Y_set. Yellow and purple lines represent the actual values X_real and Y_real, respectively.

4.1. Evaluation

In Fig. 6, set values (X_set = 180, Y_set = 175) are compared with actual values (X_real, Y_real) of the ball's position over time. When the system starts up, the ball moves from its initial position with significant oscillations, especially on the Y axis, where Y_real exceeds the set value Y_set before beginning to decrease towards the desired value; this indicates that the system reacts quickly but has a significant overshoot. After 8 sec, X_real and Y_real converge to values near their respective set points, stabilizing the X axis before the Y axis.

The setting time is 8 sec for both axes. However, the X axis tends to stabilize earlier than the Y axis. Although the Y axis reaches a relatively stable value, it exhibits minor oscillations before fully stabilizing.

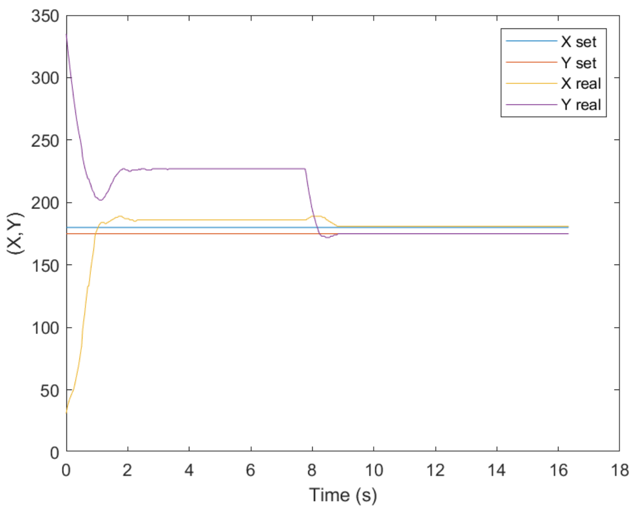

Fig. 6. Set point X= 180, Y=175

In Fig. 7, set values (X_set = 275, Y_set = 275) are compared with actual values (X_real, Y_real) of the ball's position over time. When the system starts, Y_real steadily increases and quickly reaches the set value. However, Y_real does not exhibit any overshoot during this process and continues to rise smoothly to the desired value; this indicates that the system can achieve the desired value without causing large oscillations.

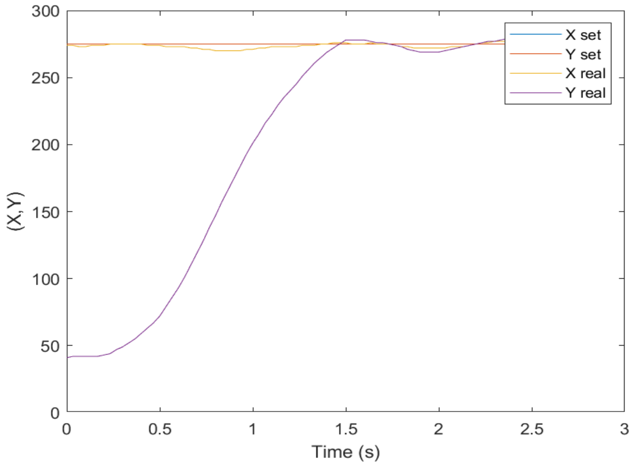

Fig. 1. Set point X= 275, Y=275

After 2 seconds, both X_real and Y_real reach a stable state close to the set value. The estimated settling time, approximately 2 seconds, is relatively quick. It indicates the system's response to the PID control signal. Nonetheless, small oscillations appear after the system reaches the set value. However, these oscillations are very minor and quickly dampen. The system is well-tuned, with only a tiny amount of residual oscillation after reaching the set value.

In Fig. 8, set values (X_set = 275, Y_set = 75) are compared with actual values (X_real, Y_real) of the ball's position over time. X_real oscillates very slightly around the set value of X_set = 275. It indicates that the system maintains good stability along the X-axis. Therefore, the PID control system effectively operates on the X-axis. It allows the ball to reach the desired position quickly and maintain stability without significant error. For the Y-axis, Y_real also oscillates around the set value of Y_set = 75, with minimal oscillations. The system stabilizes quickly after a short period. Settling time for the Y-axis is small. Y_real shows almost no overshoot or large oscillations.

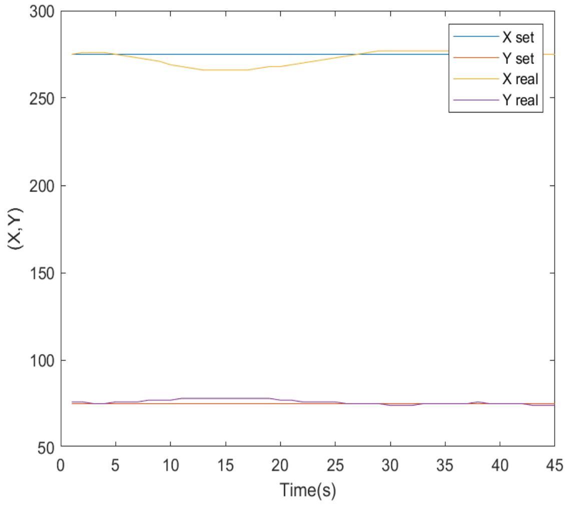

Fig. 8. Set point X= 275, Y=75

This indicates that PID control is effective in maintaining stability along the Y-axis. It ensures that the ball reaches and holds the set position efficiently. Settling time on both the X and Y axes is very fast. The system almost immediately reaches set values and maintains stability without large oscillations or static errors. This confirms that the system has been well-tuned with optimized PID parameters.

In Fig. 9, set values (X_set = 75, Y_set = 75) are compared with actual values (X_real, Y_real) of the ball's position over time.

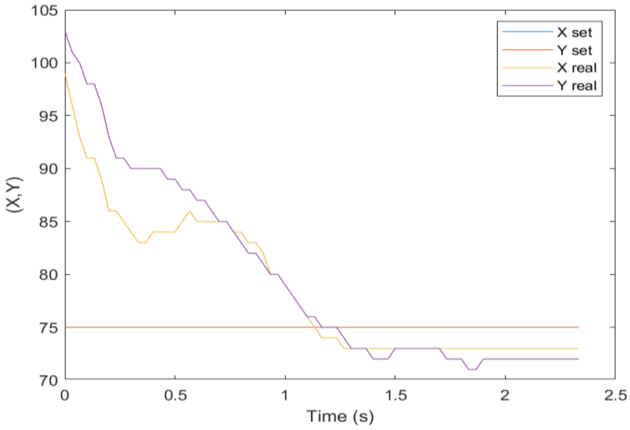

Fig. 9. Set point X= 75, Y=75

When the system starts, the ball moves from its initial position with some oscillations on both the X and Y axes. The Y axis, in particular, experiences larger oscillations than Y_real. It decreases from its initial value to below Y_set before gradually approaching the desired value. This indicates that the system has a quick response but also exhibits some overshoot.

After 2 seconds, both X_real and Y_real approach their respective set values. The X-axis stabilizes before the Y-axis. X_real reaches the set value more quickly and maintains stability. The Y-axis still shows some minor oscillations before achieving complete stability.

The X-axis's settling time is 2 sec. The Y-axis's settling time is longer due to prolonged minor oscillations before stabilizing.

By replacing a constant trajectory with a round trajectory, the results are shown in Fig. 10.

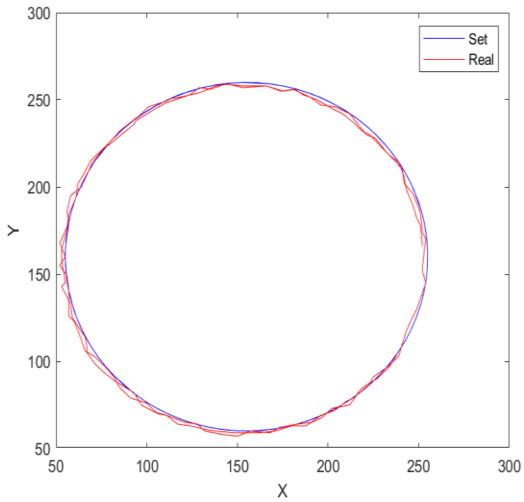

Fig. 10. Set circle

In Fig. 10, the set trajectory (Set) is compared to the actual trajectory (Real) of the ball's position over time. The centre of the circular path is at (X = 150, Y = 150). The ball exhibits slow oscillations around the trajectory while moving on a plate. It remains closely aligned with the desired path. Low speed allows the ball to follow trajectory more accurately without significant deviations. Over time, the actual trajectory stabilizes and closely follows the set trajectory. However, slight discrepancies remain, especially in curved regions where the system requires further adjustment to reduce oscillations and improve accuracy.

4.2. General Observation

From experimental results, the PID controller for BoP demonstrates good performance in controlling the ball's position to desired set values on both the X and Y axes. However, the control performance on each axis shows some differences. The system has strengths and limitations that need attention.

4.2.1. Initial Response and Overshoot

System data shows a strong initial response with a significant overshoot on the Y axis, while the X axis is more stable. This indicates that the system is highly sensitive and can react quickly to control signals. However, high overshoot should be considered to minimize unnecessary oscillations.

4.2.2. Settling Time

The settling time for both X and Y axes is relatively short. The data shows that the controller can move the ball to the desired position in a short period, reflecting the effectiveness of the PID controller in minimizing transient time.

4.2.3. Small Oscillations and Long-term Stability

After reaching the set value, the system maintains stability with small oscillations on both axes. The system shows high stability with very few oscillations, demonstrating the sound tuning of the PID parameters.

4.2.4. Differences Between Axes

The ball's motion on the X-axis is generally more stable than that on the Y-axis. This may be related to the system's characteristics or the way that PID parameters are tuned differently for each axis. Further optimization of the PID for the Y-axis may be needed to synchronize the performance between the two axes.

5. CONCLUSION

Through this research, we apply a classical controller- PID method- to balance BoP well. Also, a small calibration makes the ball follow the round trajectory. This model is preferred as a standard system for experimental testing. More methods can be developed for training and research on this system. The PID method has proved to be still effective for MIMO under-actuated models instead of only SISO and SIMO systems. The model is proven cheap and quickly prepared for laboratories in under-developed countries to satisfy the requirement of learning, training and researching.

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