Exploring PID Control in Ball-Beam Systems: A Hands-On Educational Approach

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Abstract

This paper presents a low cost, classroom experiment on constructing and testing a ball and beam system controlled by a PID (Proportional-Integral-Derivative) controller. This system is to be used in a senior level control systems class. The system consists of an Arduino microcontroller and a servo motor and a distance sensor. The experiment's goal is to tune the PID gains to balance a ball in the middle of the beam based on the distance that the IR sensor measures. The ball is set to be in the middle of the beam and the position of the ball and the speed of the servo can be manipulated based on the feedback from the distance sensor. The students were asked to study the roles of proportional (Kp), derivative (Kd), and integral (Ki) gain parameters in controlling the system dynamics. This paper presents various gain values derived from the designs of each group. This hands-on experiment gives the student a basic understanding of PID control principles and its application in real-world situations.

Keywords

Ball and Beam, PID, Control, Graduate Student Paper

Introduction

A ball and beam system is an example of a dynamic, nonlinear system requiring precise control. It is a useful example for courses in control systems. The ball rolls along a beam with the goal of keeping the ball in the middle of the beam or controlling its trajectory along the beam. A servo motor provides beam rotation by turning the connected wheel and connector rod [1]. The system is useful in demonstrating fundamental control concepts such as proportional-integral-derivative (PID) controllers [1-2]. In a first control system course focused on single input, single output control systems, PID controllers are one of the main control systems studied. PID controllers incorporate a proportional response to the input (in this case deviation of the ball from the desired position). A derivative term is added to improve dynamic response and stability by adding a response to the velocity of input (in this case the velocity of the ball). Finally, the integral term can improve steady state response (in this case the final ball position). Commercial laboratory ball and beam systems exist but can be prohibitively expensive for large class sizes. However, in recent years, microcontrollers have become more accessible and easier to use, providing a potential platform to create inexpensive ball and beam systems. Examples of ball and beam systems using inexpensive microcontrollers are available [2]. In this work, one such example was adapted to create a classroom experiment to study PID controllers [2]. Control systems courses can be math and theory heavy. By engaging in this hands-on exploration, students gain insights into the complexities of control systems engineering, preparing them to tackle real-world challenges in automation, robotics, and beyond. This paper details a classroom experiment designed specifically to immerse students in the principles of Proportional-Integral-Derivative (PID) control through the construction and operation of a ball and beam balance system.

Course

ME 682 (System Dynamics and Control Systems) is a senior level required mechanical engineering course. In Fall 2023, this course had 114 students and was taught in an active learning classroom with 20 round tables. The course is an introduction to modeling and analyzing analog and digital linear systems and designing control systems. It covers a wide range of topics including mathematical modeling of mechanical, electrical, fluid, and thermal systems, feedback concepts, transient and frequency responses, vibration analysis, system stability, and the design of feedback control systems, including the implementation of PID controllers.

The class focuses primarily on the theoretical and mathematical fundamentals of control systems. Students often complain that they struggle to see the practical applications of the material. As such, hands on activities can connect these theoretical concepts with practical applications. In addition, a hands-on activity can illustrate the differences between theory and practice but showing how unconsidered factors such as electrical noise, friction, and alignment can impact results.

The goal of this educational initiative extends beyond theoretical instruction by fostering practical skills in system dynamics, control system design, and real-time implementation. Students are challenged to develop and refine their understanding of PID parameters to achieve precise control over the ball's position on the beam, thereby mastering concepts of stability, transient response, and frequency domain analysis in a tangible setting.

Hardware and Software

The required hardware for this experiment was based on the construction tutorial available at https://electronoobs.com/eng_arduino_tut100.php [2]. The total cost of these materials was approximately $50 per setup. We were able to use some existing supplies and created 16 setups for groups of 7-9 students.

Figure 1. Required hardware

1. Arduino Uno microcontroller (Arduino Ivrea, Italy) or similar microcontroller, cost: $28
2. Sharp 2y0a21 IR sensor, cost $9
3. Futaba S3003 servomotor, cost $10
4. jumper wires
5. balsa wood
6. 3D printed parts [2]

For software, this experiment used:

1. Arduino IDE (Arduino Ivrea, Italy) – A free, open-source, C++ based integrated development environment for microcontrollers

The success criteria for this project are:

1. Implement and refine an existing closed-loop PID control algorithm.
2. Construct and program a closed-loop self-balancing ball system.

Wiring and Connection Guide

The wiring instructions for the ball and beam system are illustrated in Figure 2. The servo motor is connected to the digital pin 9 on the Arduino Uno and the IR sensor is connected to analog pin A0. Most servo motors work on pulse width modulated signal with a fixed base frequency as input, the aim of using PWM is to simulate the analog output by varying the duty cycle of the signal.

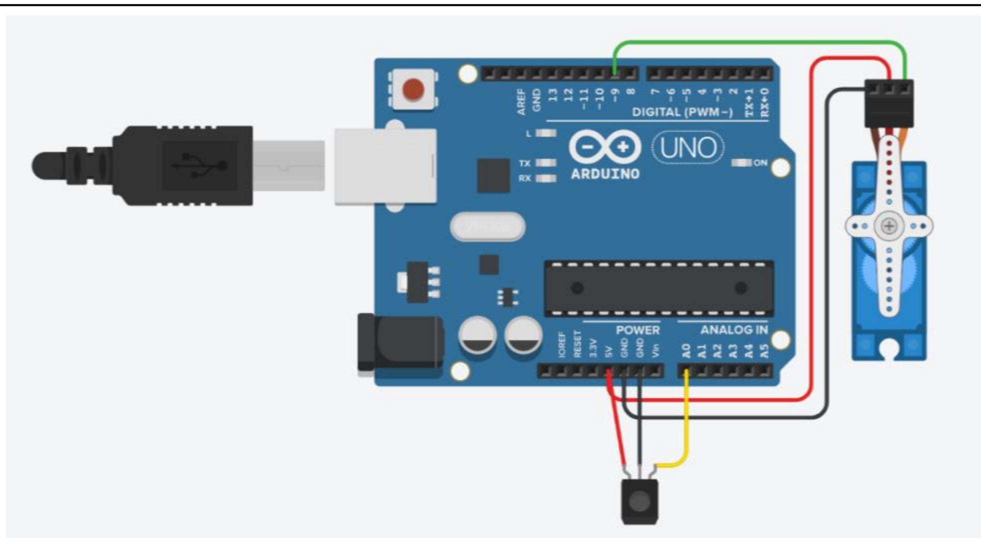

Figure 2. Wiring guide

The Sharp 2y0a21 IR Sensor

Optical distance sensors, developed over decades of optoelectronics research and innovation, include the analog distance sensor SHARP GP2Y0A21. The SHARP GP2Y0A21 is an analog distance sensor that operates on infrared (IR) light principles. The sensor contains an IR LED (Infrared Light Emitting Diode) that emits infrared light pulses as shown in Figure 3. It also has an IR receiver that detects the reflected infrared light. Based on the intensity of the reflected IR light, the sensor generates an analog voltage output. This output voltage is directly proportional to the distance between the sensor and the object in front of it. By measuring the analog voltage output, which corresponds to the intensity of reflected IR light, the distance to the object can be estimated. Typically, the sensor is calibrated to provide a linear output voltage corresponding to the distance within its specified range of 10 to 80 cm [3]. The IR sensor readings can be modeled as a function of the distance between the infrared sensor and the ball. The Proportional-integral-derivative (PID) gains were manually tuned in this case.

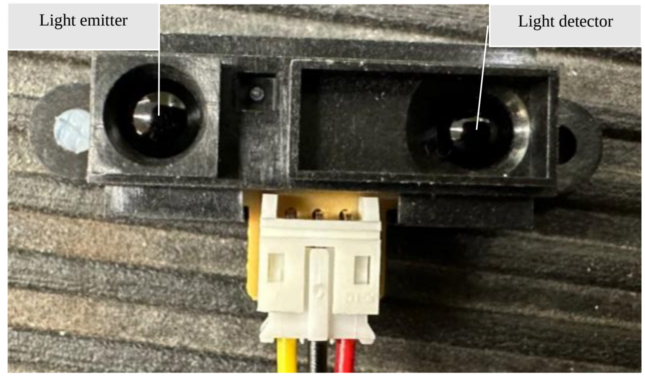

Figure 3, IR distance sensor

Ball and Beam Model

The DC servomotor is the actuator of the system. The servo motor is connected to the beam using an arm and the beam is leveled with a screw connected to the middle point of it. Figure 4 shows the schematic of the sensor and servomotor placement.

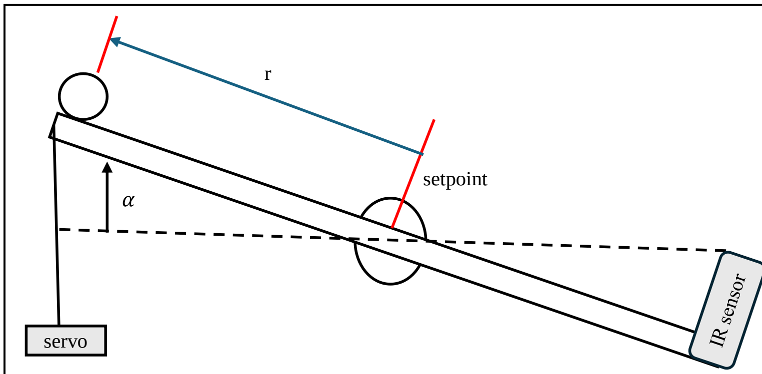

Figure 4. Ball and beam setup schematic

To study the stability of the system, they were asked to find the transfer function. This can be found using the equations (assuming small angles of rotation):

$$mr\dot{\alpha}^2 - mgsin\alpha - \left(\frac{J}{R^2} + m\right)\ddot{r} = 0$$

$$P(s) = \frac{r(s)}{\theta(s)} = -\frac{mg}{L\left(\frac{J}{R^2} + m\right)}\frac{1}{s^2} \quad [\frac{m}{rad}]$$

where m is the ball mass and R is the ball radius. g is the gravitational acceleration. L is the beam length and J is the moment of the inertia. θ is the servo angle and d are defined as the offset between the lever arm and the servo center of rotation when the angle θ is small the relation between θ and α can be considered $\alpha = \frac{d}{L}\theta$. The state space model can be defined as below.

$$\begin{bmatrix} \dot{r} \\ \ddot{r} \\ \dot{\alpha} \\ \ddot{\alpha} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{mg}{\left(\frac{J}{R^2}+m\right)} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} r \\ \dot{r} \\ \alpha \\ \dot{\alpha} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} r \\ \dot{r} \\ \alpha \\ \dot{\alpha} \end{bmatrix}$$

The controller can be modeled with the equation:

$$PID\ output = K_p * Error + K_i * \int_0^t Error + K_d \frac{dError}{dt}$$

Where K_p, K_i and K_d are all non-negative coefficients for the proportional, integral, and derivative terms. The students were asked to use this model and root locus methods to examine what the K_p, K_i and K_d values might be based on the theoretical materials presented in the class.

Figure 5 shows a prototype of the ball and beam system. However, the students were assigned to sixteen different groups and each group proposed their own unique structure. The different sizes for 3D printed discs were provided in case the students need slower or faster movements. The students were asked to consider how their physical system compared to the theoretical model and adjust the model as appropriate.

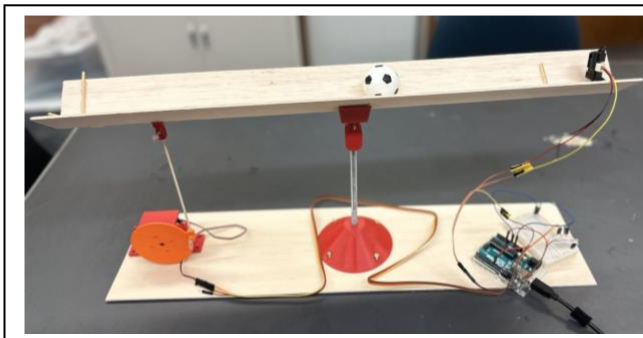

Figure 5. Ball and beam prototype

Results

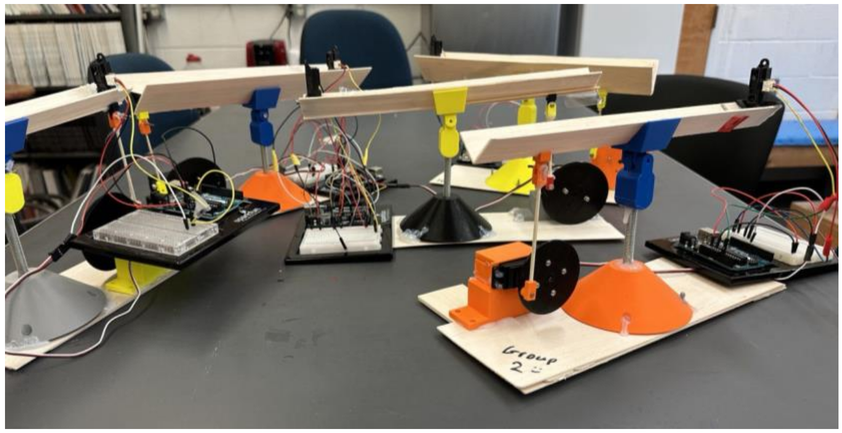
Figure 3. Prototypes created by student groups

The students adjusted their design by varying the length of lever arms and modifying the V-shaped beam. Since the basic design was provided in the tutorial, their focus was on refining their setup to incorporate these changes. Some groups encountered instability in the base, resulting in unexpected shaking during testing. 56% of groups were able to achieve stable control of the ball.

Throughout their experimentation and discussions with both their group and the instructor, they faced challenges with the distance sensor's performance. They noted occasional inconsistency between the intended and actual machine behavior, particularly concerning the sensor's consistency in detecting the ball, especially at larger distances. Adjustments to the distance error threshold were crucial to adapt to their specific model, as discovered during thorough testing. It is suggested to add a capacitor as a filter at the sensor output. Also, by adding a calibration step to the distance sensor, the students can achieve more accurate readings from the sensor.

The PID controller uses input from the distance sensor to move the servomotor and change the system output (displacement of the ball relative to the desired position). Managing servomotor angles and positioning posed additional challenges for the students, which they addressed by closely following the tutorial step-by-step [2]. They utilized Arduino software to customize K_p, K_i, K_d, and sensor distance values, aiming to optimize the system's overall performance. By tweaking the gain values separately, they discovered that K_p caused the beam to oscillate as the ball is either too close to the sensor or too far. Changing K_d is a reaction to the speed of the ball and with a PD controller in the middle we can get the ball to the setpoint and then stop it there to balance the whole setup. Table 1 shows the gain values were different for each group. While K_p and K_i were relatively similar, K_d varied significantly between the groups.

Among the groups, group sixteen's model was the closest to model prediction, it is worth mentioning that the parameter values for this group as an example are m = 0.0027 kg, R = 0.02 m, L = 0.3 m, and the estimated value for d is 0.004 m. 46% of the class population achieved the stability for their system and Table 1 shows all the PID gain values for all the successful and unsuccessful designs.

Table 1, PID gain values reported by groups for each group's design (with varied designs)

Group	K_p	K_i	K_d
1	2.5	0.1	50
2	8	0.2	3100
3	10	0.3	2500
4	7	0.2	250
5	8	1	8000
6	9	0.3	32.1
7	5	0.15	2250
8	5	0.1	175
9	2	0.15	1500
10	8	0.2	2000
11	4	0.2	10
12	4	0.8	700
13	4.8	1	3300
14	3	0.1	700
15	8	0.2	3100
16	5	0.15	2250

Deliverables and Assessment

This lab had two required deliverables, a group presentation of their working prototype (25 points) and an individual report (25 points). In the presentations, groups were asked to show how their prototype worked and discussed what worked, what didn't work well, and improvements they might make if they had the opportunity. Students received full credit for actively participating in the presentation or through a make-up communication if they missed class. For the individual report, groups could work together (and submit the same answers) but each student had to submit individually to assure everyone was invested in the assignment. For the report, students were asked to reply to the following prompts:

1. Describe the process of your design. What are the elements included? What was the code? Did you do anything that was different from the given video? What things didn't work well? Were you able to fix anything that didn't work well? What process did your group use to access the device and fix any issues?
2. Upload a block diagram that illustrates how your system works. What is the feedback? What are the transfer functions?
3. Create a mathematical model of your system. Show your work for how you derived the equations of motion (and therefore transfer functions). Start with a free body diagram of the mechanical system.
4. Using the block diagram and transfer functions, what do you expect the response of the system to be to an impulse input (sudden tap on the ball)? Derive a response. Give the Kp, Kd, and Ki, you used experimentally, how would you expect your system to behave.

5. What Kp, Kd, and Ki (proportional, derivative, and integral) gains did your group find worked best for control of the ball?
6. Upload a photo of your system.
7. Upload a video of your group's working prototype.

For the most part, grading of these deliverables reflected active participation in the project and demonstration of effort. Exam questions were also used to assess understanding of PID controllers.

Conclusion

This active learning session enhanced comprehension across several subjects, including microcontroller programming and the experimental development, modeling, and testing of control systems. The goal was to educate students on PID controllers' fundamentals, their functionalities, and practical uses through hands-on activities. While the experiment garnered positive feedback from students, there are areas for enhancement, particularly in refining the clarity of instructional materials and providing more structured guidance during practical exercises. While all groups were able to construct and run a ball and beam system, only 56% were able to successfully achieve steady control of the ball position. Characteristics that defined these successful groups included getting started earlier and greater perseverance and troubleshooting construction and sensing issues. Some of the major problems observed include unintended movement in the system (wobbly base, misalignment in the servomotor connection, etc) and issues when the ball was either too close or too far from the sensor. In future years we plan to refine this experiment, improving instructional materials and starting the project earlier in the semester to allow more time for students to work through construction issues.

References

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Sara Wilson

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