Abstract

A system is presented as an archetypal example of a dynamic control system in which an automated controller attempts to stabilize a ball resting on a beam. This was accomplished by measuring the ball's position along the beam and the angle of the beam using an ultrasonic and gyroscopic sensor, respectively. These measurements were supplied to a cascade-style PID control loop that maintains a set position. Ideally, the controller maintains the ball's positional setpoint when the system is disturbed (i.e. manually nudging the ball). In practice, the system is semi-stable, avoiding collisions with the sensors. The system's actuator is a servo motor attached to a spool of string, which is connected to each of the beam's ends. The system controller is an ESP32 device programmed using micropython.

Introduction

The control of unstable systems is a critical challenge in many control applications. Ball-and-beam systems, commonly studied in control theory (e.g., Saad, 2017), are widely recognized for their nonlinear dynamics, making them an ideal case study for exploring advanced control strategies. Studies have demonstrated the effectiveness of similar systems, such as Găşpăresc (2014) with the use of the same Parallax Ping ultrasonic sensors used in the present system. The novelty, however, lies in the unique use of spools and thread, driven by a servo motor, to actuate a torque on the beam.

This project's impact is diverse. It enhances public welfare by offering an educational opportunity for students to better understand PID controllers, which are ubiquitous in modern automated systems. As more students grasp the underlying concepts, the world's workforce will be better equipped to create automated systems, enabling further refinement of global manufacturing. The attractive colors and engaging concept inspire observers to explore STEM fields, positively impacting social factors. The intriguing and interactive design also encourages others to learn about PID control. The project did require the consumption of PLA plastic for 3D printing and the use of four 9-volt batteries, both of which produced potentially harmful environmental waste. As a learning tool, however, it remains cost-effective by allowing students to experiment with PID controllers and benefit from rapid prototyping, which reduces time costs.

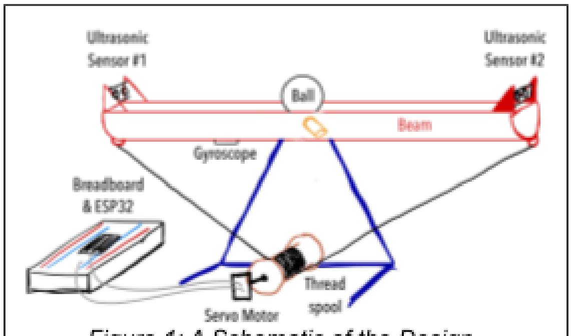

Figure 1: A Schematic of the Design

Theory

The final product comprises two main components: the physical system and the software controlling it. The physical system (Figure 1) includes a 3D-printed frame with a 420 mm beam hinged at the center. With a working length of 405 mm, it features ultrasonic sensors at each end that measure the position of the ball and feed that data to the controller. The beam also has a gyroscope for measuring the beam's angle. Strings connect each end of the beam to a 3D-printed spool inside the base. The spool is driven by a continuous MG90S servo motor; all components are wired to an ESP32 microcontroller.[1] Key system parameters are listed in Table 1.

L	Length of beam
m	Mass of ball
d	Diameter of ball
θ	Angle of beam
ω	Servo angular velocity

Table 1: Key Parameters

The on-board ESP32 device contains a micropython script encoding a cascade-type PID control loop. The device also contains packages that simplify the use of components such as servo motors and ultrasonic sensors. The main control program allows for open loop (manual) and closed loop (automatic) control. Manual mode accepts input from a user-controlled joystick, rotating the beam based on the

[1] A circuit diagram or detailed picture is available upon request.

joystick’s movements. This function is extremely useful for proof-of-concept experiments and testing the actuation of the system as a whole. In automatic mode, the program uses cascade control with an inner and outer loop to control the ball's location. The outer loop uses ultrasonic sensors to determine the ball's position and a PID controller to calculate a beam angle setpoint. This beam angle set point is the input for the inner loop, which receives the actual beam angle from the gyroscope. The inner controller then calculates the required angular velocity for the servo motor based on the difference between the desired and actual beam angles. This angular velocity is outputted to the servo motor.

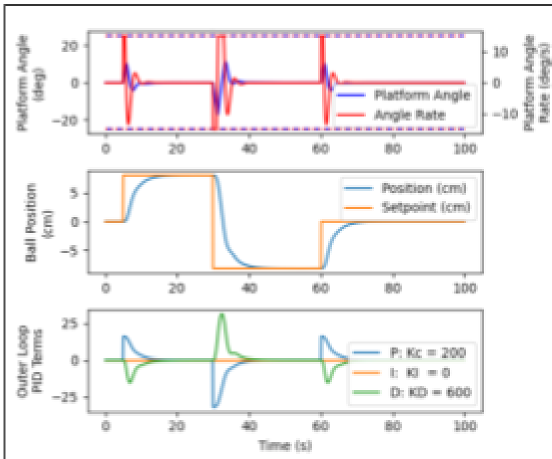

Figure 2: Simulation of Closed-Loop Control

Discussion/Recommendations

This project presented several challenges, including sensor and actuator limitations. For example, the output frequency of the ultrasonic sensors is the same: the measurements times were alternated to avoid interference. The sensors produced noisy positional readings, necessitating the use of alpha and gate filters. A significant source of this error stemmed from the shape of the ball: this was mitigated by using a 3D-printed cylinder designed to roll along the beam’s grooves. To prevent damage from extreme torque, the code incorporated a safety function that deactivated the motor if the beam angle exceeded safe limits. Initially, the system exhibited aggressive responses, often propelling the ball to one side. Careful tuning of parameters and the addition of cascade PID control significantly improved system stability. The intrinsic system delay was minimized by increasing the sampling frequency, removing unnecessary filters, and refining model calculations.

	K_C	K_I	K_D
Outer Loop	0.25	.095	2.4
Inner Loop	-3.0	0.0	-0.5

Table 2: Optimal Tuning Parameters

Simulations using simplified physics indicated that a stable system was attainable (Figure 2); use of open-loop control showed that positional stability was mechanically possible. However, it quickly became clear that the system was not equipped to attain stability under closed-loop control. The sensors’ intrinsic uncertainty acted as large, erratic disturbances, and physical limits in motor speed limited responses to extreme disruptions. However, through careful tuning, parameters that produced a semi-stable system[2] were discovered. Table 2 displays these parameters, and Figure 3 displays the results of one closed-loop test.

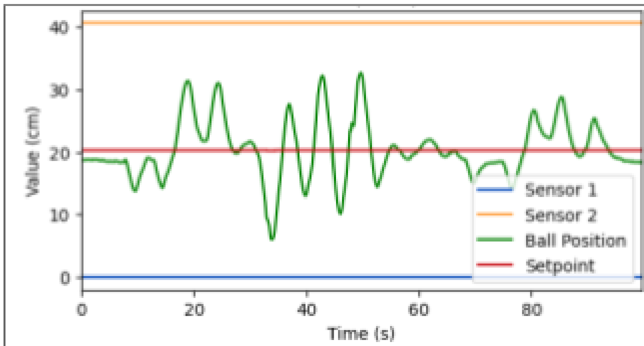

Figure 3: Closed-Loop System Response

Conclusion

This project successfully demonstrated the design and implementation of a ball-and-beam system as an educational tool for studying PID control in dynamic systems. By employing cascade-style PID control, filter optimization, and safety mechanisms, the system achieved semi-stable performance in the face of significant challenges, namely sensor interference, noisy data, and actuator limitations. This project serves as a valuable resource for understanding advanced control strategies, emphasizing both the practical applications and complexity of real-world systems. Future work could explore alternative sensing and actuation methods to further improve system responsiveness and robustness.

[2] A “semi-stable” system was defined as one in which the ball is maintained near the setpoint, never colliding with the beam’s endpoints.

References

Saad, Mustafa. (2017). Design and Implementation of an Embedded Ball-beam Controller Using PID Algorithm. Universal Journal of Control and Automation. 5. 63-70. 10.13189/ujca.2017.050402.

G. Găşpăresc and A. Gontean, "Performance evaluation of ultrasonic sensors accuracy in distance measurement," 2014 11th International Symposium on Electronics and Telecommunications (ISETC), Timisoara, Romania, 2014, pp. 1-4, doi: 10.1109/ISETC.2014.7010761.

Final Presentation

https://youtu.be/AO3dtjWEcSs
Slideshow available upon request.