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# An Optimized Ball and Plate System Based on a PID Controller

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## Abstract

This study gives an in-depth look into the well-known ball and plate system, which uses sensors, actuators, and controllers to keep a rolling ball balanced on a flat platform. The theoretical investigations and analyses underlying the ball and plate system are clarified, including the system's mathematical and physical modeling, as well as a full explanation of the components involved. The goal of our project is to design a closed-loop PID controller to achieve ball balancing on the platform. A resistive touch screen is used in the project as a sensor to detect the ball's current horizontal and vertical coordinates. The PID controller then compares these coordinates to the intended position and controls two DC servo motors acting as actuators, tilting the platform to achieve and maintain the desired ball position. The system's goal is to keep the ball at a specified fixed location in the face of any disruptions (disturbance rejection). Particle Swarm Optimization (PSO) is used to tweak the PID controller settings, which optimizes an objective function that minimizes the Integral Absolute Error (IAE) in both the x and y coordinates of the ball's position on the plate. This project is an implementation of the PID controller, which is used in a variety of real-world applications such as balancing robots, drones, and temperature control systems. The fundamental goal of developing such a system is to get a full educational knowledge of balancing systems and their operating principles, which are important in many sectors of life and can be improved further for future usage. Furthermore, the introduction of an optimization approach to improve the system's reaction to disturbances is regarded as a significant addition to the area.

## Keywords
Control, Ball and plate, PID, motors, IAE, automation, operations

## 1. Introduction
The primary goal of this project, named "Optimized Ball and Plate System," is to address the challenge of obtaining effective balance and control, of a free-rolling ball on a flat plate by using servo motors to tilt the platform. The aim

is to build and implement a full and dynamic control system capable of overcoming any budgetary limits encountered by students throughout project execution.

To accomplish this goal, a meticulous approach will be taken to model and simulate the system, considering the various physical and mathematical aspects involved. The dynamic control system will be engineered with the intention of ensuring precise and stable control, over the ball's position on the plate.

One of the critical aspects of this project is the fine-tuning of the PID (Proportional-Integral-Derivative) controller parameters. The success of the system hinges on achieving optimal parameter values that can effectively regulate the ball's motion and maintain stability during the steady-state phase. By carefully adjusting these parameters the project aims to optimize the performance of the ball and plate system, enhancing its ability to maintain the desired position of the ball and resist disturbances.

Moreover, this project recognizes the significance of overcoming financial limitations that students often face. The team will explore cost-effective solutions and resource-efficient techniques without compromising the overall functionality and performance of the system. This approach will allow for practical implementation and encourage the replication of the project in educational settings with limited resources.

By addressing these challenges and refining the control system, the project seeks to advance the understanding and application of dynamic control systems, particularly in the context of balancing and control mechanisms. Ultimately, the project aims to contribute to the field by demonstrating the effectiveness of an optimized ball and plate system and inspiring further developments in this area of research.

Our objective is to develop a sophisticated balancing system utilizing a ball and a plate. This system incorporates a well-known controller known as PID (Proportional Integral Derivative) to effectively address any unexpected ball movements and swiftly restore it to its desired position. This project allows us to put into practice the control concepts that we have extensively studied.

The core mechanism of the system revolves around the implementation of negative feedback. This feedback loop acts as a compensatory mechanism, actively countering any errors or disruptions that the system may encounter. By employing negative feedback, the system aims to mitigate issues such as overshooting, steady-state error, and rise time. It highlights the fact that even a slight modification in the input can have a substantial impact on the output.

The practical applications of the ball and plate system are manifold. Firstly, it serves as a valuable tool for educational purposes, particularly in laboratory settings within universities. It can be utilized to teach students the principles of control courses, providing hands-on experience and enhancing their understanding of control systems.

Additionally, the knowledge and insights gained from this project have the potential to be applied in the development of advanced PID controllers. These controllers can be integrated into drones, augmenting their safety and security measures. By incorporating the ball and plate system's principles into drone technology, it becomes possible to enhance their stability and ensure reliable operation in various applications.

In essence, our project is concerned with the development and implementation of a cutting-edge balancing system based on a ball and a plate. We can successfully manage unexpected ball motions and exploit the control ideas we have learned by using the PID controller. The inclusion of negative feedback resolves faults and disturbances, and the system's practical uses range from educational settings to improving drone safety and security.

## 1.1 Objectives

The project encompasses several primary objectives, which are outlined as follows:

1. **Develop and Implement a PID Controller**: The foremost goal of this project is to design and deploy a PID (Proportional Integral Derivative) controller specifically tailored to regulate and control the movement of the ball on the plate. By leveraging the PID controller's control algorithm, the system will effectively counteract any deviations from the desired ball position, ensuring stability and precise control.
2. **Optimize PID Parameters**: A key objective is to fine-tune the PID controller's parameters to achieve the desired output and enhance system performance. Through careful parameter adjustment, the project aims to optimize the response of the ball and plate system, minimizing overshoot, reducing steady-state error, and

improving response time. This process involves utilizing analytical techniques, experimental data, and systematic iterations to arrive at the optimal parameter values.

3. **Comparison of Real-Time and Theoretical Response**: Another significant aim of the project is to conduct a comparative analysis between the real-time response of the ball and plate system and its corresponding theoretical response. This comparative study allows for an evaluation of the system's performance, providing insights into any disparities, potential limitations, or areas for improvement between the expected and observed behavior of the system. By examining these differences, the project seeks to gain a deeper understanding of the system dynamics and the practical aspects influencing its performance.

By pursuing these objectives, the project aims to successfully implement a PID controller that can regulate the ball's movement on the plate, optimize the PID parameters for improved performance, and provide insights into the similarities and differences between the real-time and theoretical responses of the system.

## 2. Literature Review

The ball and plate method has become one of the most well-known control techniques in recent years, particularly among undergraduate students, since it gives a fantastic chance to learn expertise in several domains, such as mechanical, electrical, and computer engineering.. Therefore, this system has been implemented and utilized by some of the students in their graduation projects and even by professional engineers.

### Ball and Beam System

The ball and beam system, like the ball and plate system, is initially an unstable, nonlinear, open loop system that requires active feedback control to stabilize. The theoretical modelling of the ball and beam system is depicted in Figure 1. The ball and beam system, as illustrated in Figure 1, consists of a DC motor, lever arm, ball, beam, and support. Because the ball has the same radius as the beam width, it can only move along the length of the beam. The servo motor is attached to one end of the beam by the lever arm, while the other end is connected to a permanent support. The lever arm moves up and down by providing an electrical control signal to the DC servo motor. This electrical signal causes the servo gear to turn by the angle ($\theta$) to tilt the beam by an angle ($\Phi$). The ball rolls along the beam with an acceleration proportional to the beam angle $\Phi$ (Taifour, A. Almahdi, H. Et al. (2017)).

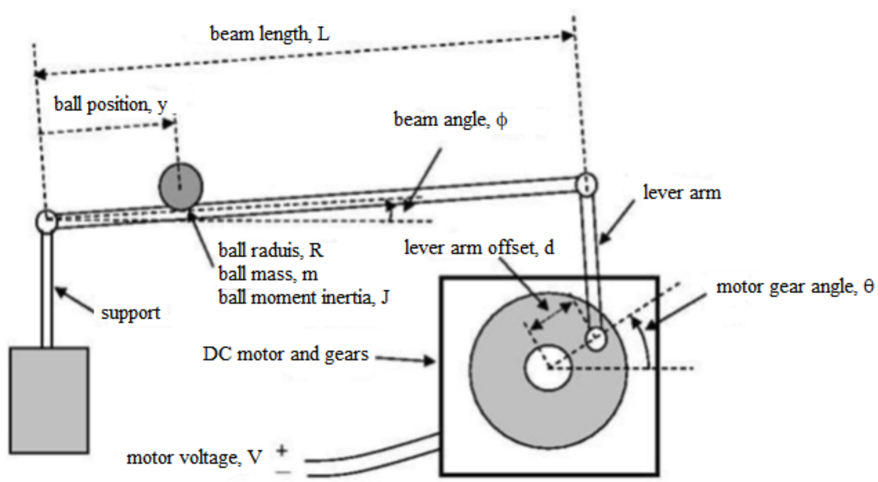


Figure 1: The model of ball and beam
(Utkarsh Saini, 2017)

The ball will continue to travel until it falls off the beam if there is no controller. As a result, a controller is created to alter the location of the ball. The following Equation (1) depicts the transfer function of the ball position y(s) to the motor gear angle $\theta(s)$ (Taifour, A. Almahdi, H. Et al. (2017)).

$$\frac{y(s)}{\theta(s)} = \frac{mgd}{L(m + \frac{J}{R^2})} \frac{1}{s^2} [\frac{m}{rad}] \qquad \text{Eq.2.1}$$

## Previous Ball And Plate Researches And Studies

In previous reports and papers, various components have been employed, each exhibiting distinct functionalities and offering varying levels of accuracy and quality.

***Different types of sensors that can be used to get the ball position***

- Overhead digital camera with image processing software such as MATLAB or Python. This method is not very reliable since it requires additional software and work to process the image.
- Resistive Touch screen: It is a little difficult to implement because of the limited sources, but it's financially affordable for a student and provide reliable and relatively accurate results. It needs a dedicated controller if used within a PC development environment. Whereas some microcontroller such as Arduino can be used also as touch screen controller.
- 3D motion tracking of the rolling ball. This method used infrared-ultrasonic transponder connected to the ball. This method is clean measurement and very accurate, but it is hard to use, very expensive and cannot be implemented by students (Awtar, S. Bernard, C. Bernard, N. et al (2002)).

Based on the study of the advantages and disadvantages of sensing methods, we have chosen a resistive touch screen to be the sensor in our project since it was the most convenient choice because it is reliable, affordable and gives good results.

***Different controllers that used to stabilize the system***

- The PID controller (proportional, integrand and derivative controller). The PID controller is the most famous and used controller. Since it is a very effective controller, and it has proved its efficiency by reducing the error. Also, the PID controller has built-in libraries in MATLAB and Arduino which make it easier to implement. The PID controller requires a mathematical modelling of the system to tune its parameters.
- LQR controller (Linear Quadratic regulator): the LQR gives the desired output with less control effort. However, LQR is very difficult to design for a non-linear complex system, especially for beginners; therefore, it has not been implemented widely in this project.
- Fuzzy logic controller: one of the modern types of controllers and it is easier to implement for nonlinear systems since it does not need a mathematical modelling. The issue is that the generation of the rule table necessitates the help of an expert, or it will provide inaccurate results, and it requires thorough knowledge in the field (Kasim,A.Hadad, H. and Albitar, C. (2015)).

According to the mentioned characteristics of each controller, we chose to design a PID controller because it is relatively simple to design and tune, has sufficient resources, has built-in libraries in many programming environments and imbues the student with a lot of knowledge in mathematics and control.

***Different environment to program and implement the controller***

- MATLAB/Simulink: it has a PID built in library, it can be used for image processing when using a camera as a sensor, but in the case of a touch screen it is not very reliable since it needs an additional controller to convert the values generated by the touch screen from analog to digital (Kaplan, K. (2016)).
- LabVIEW development environment provides a graphical programming way to visualize the system. LabVIEW is the same as MATLAP/Simulink needs additional dedicated controller for the touch screen to get the digital values of the coordinates (Appleton, B, Rijal, R. et al. 2017).
- Arduino Software IDE: is a well-known integrated development environment used for Arduino chip. It has a built-in library for servo motors, touch screens and PID controllers. Therefore, there is no need to use additional controllers for the touch screen (Itani, A. (2017)).

Considering the previous information as well as the use of the touch screen as a sensor and the DC servo motors as actuators along with the PID controller, we concluded that use of Arduino microcontroller is the best option for our project.

***The actuators used in previous systems***

For the actuators, almost all studies and researches have used servo motors either (DC or stepper) because they have high torque, precision and speed capabilities, able to reverse their direction with high speed due to their low inertia, do not heat or lower the speed and have the ability to accelerate and decelerate quickly (Awtar, S. Bernard, C.

Bernard, N. et al (2002)).
For our project we chose DC servo motors since they have proven their high efficiency in the control field.

**Previous Systems Implemented by Different Parties**

***System 1***

This system was built as a final year project by the students of Fontys University of Applied Sciences. The system used a resistive touch screen in order to get the position feedback of the ball and a dedicated touch screen controller to convert the analog values that resulted from the touch screen to digital values which can be used by the PC. The touch screen controller conveys the ball coordinates to the PC through RS-232 cable instead of USB due to its simple protocol. Then the coordinates of the ball are sent to LabVIEW development environment in order to control the servo motors (the actuators). A controller is implemented in the LabVIEW by generating a PWM (Pulse Width Modulation) signal with the help of PID controller. Figure 2 shows the construction of the system (Appleton, B, Rijal, R. et al. 2017).

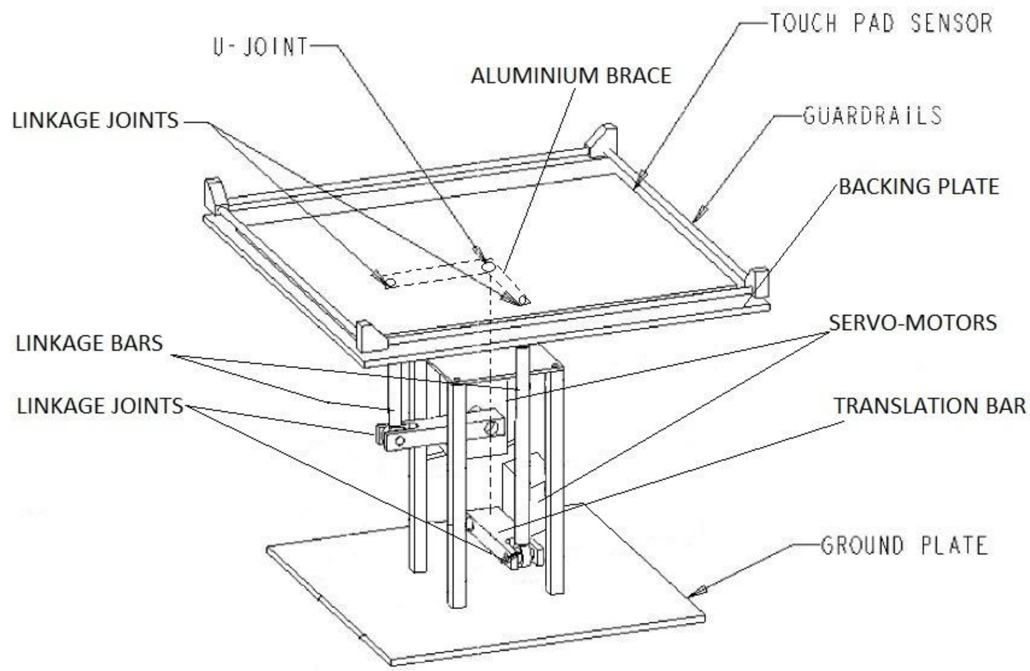


Figure 2: The mechanical construction of a previous ball and plate system
(S. Awtar et.al., 2002)

***System 2***

This system was done by the engineering Faculty of Kocaeli University. The system used the fuzzy logic to control and stabilize the system. In this system a digital camera is used as a sensor. A picture of the platform is captured by the camera and then processed using image processing in MATLAB/Simulink environment in order to obtain the ball's x and y coordinates. When the coordinates are determined, fuzzy logic is implemented also by MATLAB/Simulink to generate the control output. The generated control output then is sent to a microcontroller that controls the servo motors which tilt the platform according to the results. Figure 3 presents the mechanical design of this project (Kaplan, K. (2016)).

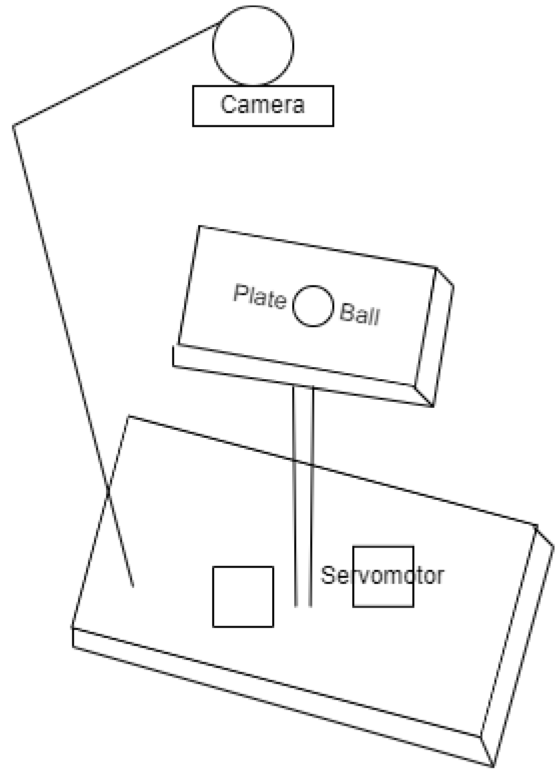


Figure 3. The mechanical design of the ball and plate system using a camera
(Kuncan et al., 2006)

## 3. Results and Discussion

### 3.1 Numerical Results

The system design stands as the most crucial and pivotal aspect of this project, playing a pivotal role in its successful completion. It encompasses a comprehensive examination of the project's structure, the selection and integration of various components, the development of a system circuit diagram, and the creation of a program flowchart. The importance of this phase cannot be overstated, as it lays the foundation for both the hardware and software implementation, ensuring a streamlined and efficient execution of the project.

Within the system design section, thorough attention will be given to seamlessly connect the hardware components. This entails establishing robust and reliable connections between different elements of the system, facilitating effective communication and synchronization among the various parts. By ensuring a sound hardware integration, the project can function cohesively and efficiently.

Simultaneously, equal importance will be placed on the software implementation, particularly in programming the controller. The aim is to develop a software framework that simplifies the implementation process, making it more accessible and user-friendly. This involves writing clean and well-structured code, optimizing algorithms, and integrating efficient control strategies to achieve the desired functionality.

The system design section serves as a comprehensive guide, providing detailed insights into both the hardware and software aspects of the project. It presents a holistic view of the project's structure, components, circuit diagram, and program flowchart. By exploring these essential elements, readers and project evaluators will gain a thorough understanding of how the project is constructed, the interdependencies between components, and the systematic approach taken to ensure a successful implementation.

Overall, the system design section plays a critical role in this project, laying the groundwork for the seamless integration of hardware components and the development of efficient software implementation. It serves as a blueprint for the entire project, ensuring clarity, coherence, and effective execution.

## Project Structure

The DC motor is a mechanical device that generates rotary motion. It operates on the PWM (pulse width modulation) principle, which means that its rotational movement is controlled by the pulses provided to its control pin. A DC servomotor is made up of a variable resistor and a gearbox that converts the motor's speed into high torque. It is typically employed when strong acceleration, quick reaction, small size, and high output torque are required (Figure 4).

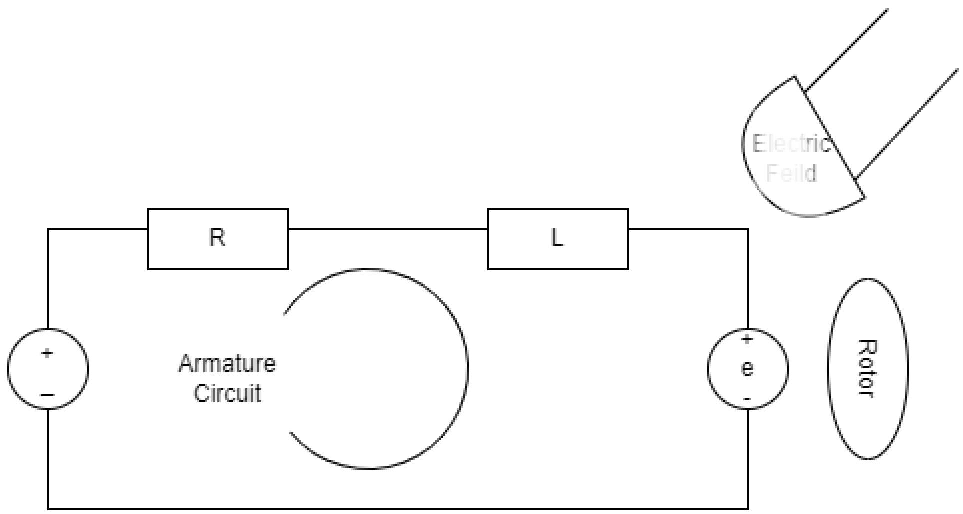


Figure 4. Circuit diagram of DC motor
(Mehta et al., 2023)

First and foremost the DC motor generate torque from the current by the equation

$$T = Kt \times I \quad \text{Eq. 4.1}$$

Where:
$Kt$ is the torque constant.
$I$ is the current.
The equation (4.1) shows that the current is proportional with torque, This means that any increase in the current will lead to increase in torque and vice versa.
The output current is proportional to the input voltage and the proportional factor is $Ka$:

$$I = Ka \times v \quad \text{Eq. 4.2}$$

Using the figure (4-1) and according to newton's law

$$Ja = T + Tf \quad \text{Eq. 4.3}$$

$a$ is the acceleration
$J$ is moment of inertia
$Tf$ is the opposing friction

$$a = \frac{d\omega}{dt} \quad \text{Eq. 4.4}$$

$$\omega = \frac{d\theta}{dt} \quad \text{Eq. 4.5}$$

Where ω is the angular velocity
θ is the angular defiance
the acceleration is the derivative of the speed.
Taking the Laplace Transform of the two equation (4.4) & (4.5):

$$\omega = \frac{1}{s} \times a \quad \text{Eq. 4.6}$$

$$\theta = \frac{1}{s} \times \omega \quad \text{Eq. 4.7}$$

Substituting equation (4.6) into (4.7) we get the following

$$\theta = \frac{1}{s^2} \times a \quad \text{Eq. 4.8}$$

Substituting equation (4.3) into (4.8) and neglecting Tf we will get

$$\theta = \frac{1}{s^2} \times \frac{T}{J} \quad \text{Eq. 4.9}$$

Substituting equation (4.1) into (4.9) we get the following

$$\theta = \frac{1}{s^2} \times \frac{Kt \times I}{J} \quad \text{Eq. 4.10}$$

Substituting equation (4.2) into the above equation

$$\theta = \frac{1}{s^2} \times \frac{Kt\, Ka\, v}{J} \quad \text{Eq. 4.11}$$

The transfer function for the servo motor system, taking θ as the output and v as input for the system is:

$$\frac{\theta}{v} = \frac{Ka\, Kt}{J\, s^2} \quad \text{Eq. 4.12}$$

The transfer function above will be affected by another factor which is the gear ratio (Kg) so the transfer function will be modified into another one which is:

$$\frac{\theta}{v} = \frac{Ka\, Kt\, Kg}{J\, s^2} \quad \text{Eq. 4.13}$$

The equation (4.13) is the transfer function for rotational displacement (θ) as an output but if we want to take angular speed (ω) as an output for transfer function there will be some changes and the transfer function will become [Ogata, K. (1970)].

$$\frac{\omega}{v} = \frac{K_t}{s^2 JL + sJr + K_b K_t} \quad \text{Eq. 4.14}$$

## Ball and Plate System

The main goal of the project is to keep the ball stable on a flat plate with predefined bounds. The platform's sensor will work to identify the position of the ball on the plate surface, and if the position changes, the sensor will send a signal to the controller to bring it back to the intended spot. The servo motor will operate in tandem with the controller to regulate the ball's position and maintain it inside the bounds.

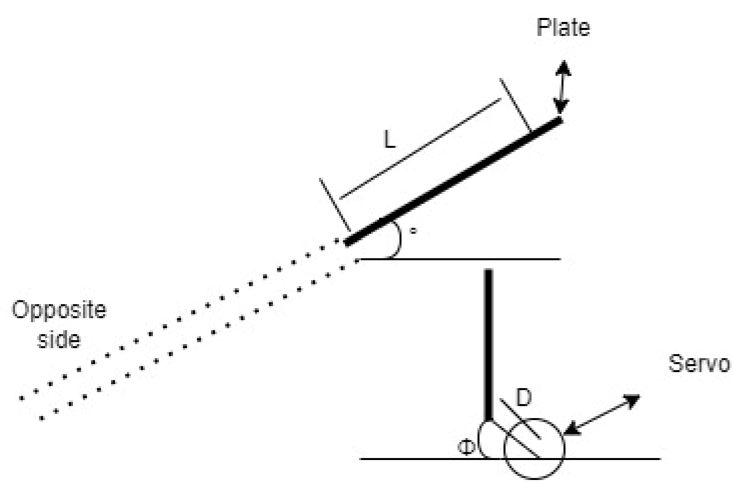


Figure 5. Ball and plate model
(Cham Ham and Taufiq, 2015)

From the Figure 5, we can determine the transfer function for the moving ball on x direction considering the following:
x is the distance covered in x direction.
θ is the angle of the plate.
α is the angle of the motor.
m is the mass .
L is the length of the plate.

$$F_g = mgsin(\theta) \quad \text{Eq. 4.15}$$

$$F_N = mx\theta^2 \quad \text{Eq. 4.16}$$

$$F_{ball} = \frac{J}{R^2} + mx \qquad \text{Eq. 4.17}$$

$$F_N = F_{ball} + F_g \qquad \text{Eq. 4.18}$$

$$mx\theta^2 = \frac{J}{R^2} + mx + mgsin(\theta) \qquad \text{Eq. 4.19}$$

$$\frac{J}{R^2} + mx + mgsin(\theta) - mx\theta^2 = 0 \qquad \text{Eq. 4.20}$$

If we assume that there is a small change in the plate coordinates.

$$\theta \approx 0 \qquad \text{Eq. 4.21}$$

$$sin(\theta) = \theta \qquad \text{Eq. 4.22}$$

$$cos(\theta) = 1 \qquad \text{Eq. 4.23}$$

$$\frac{J}{R^2} + mx + mg\theta = 0 \qquad \text{Eq. 4.24}$$

For better calculations we may substitute the motor angel instead of the plate angle.

$$\theta = \frac{r}{L}\alpha \qquad \text{Eq. 4.25}$$

Substitute the above equation in equation number (4.24)

$$-mg\theta = \frac{J}{R^2} + mx \qquad \text{Eq. 4.26}$$

$$-mg\frac{r}{L}\alpha = \frac{J}{R^2} + mx \qquad \text{Eq. 4.27}$$

$$X = \frac{-mg\frac{r}{L}\alpha_y}{\frac{J}{R^2}+m} \qquad \text{Eq. 4.28}$$

This is the mathematical expression for the system, but only in one direction, x. However, because the angle changes in both directions (x and y) in this system, the formula above may be utilized in both directions independently, which means:

$$Y = \frac{-mg\frac{r}{L}\alpha_x}{\frac{J}{R^2}+m} \qquad \text{Eq. 4.29}$$

where $\alpha_x$is the angle of the motor in y direction and $\alpha_y$is the angle of the motor in x direction. The ball can be either hollow or solid ball. each kind of them have different inertia and they are given by the equations:

$$J_{solid} = \frac{2}{5}mR^2 \qquad \text{Eq. 4.30}$$

$$J_{hollow} = \frac{2}{3}mR^2 \qquad \text{Eq. 4.31}$$

substitute these formulas in Equations (4.28) and (4.29). Since we are going to use a solid ball we are not going to explain about the hollow.

$$X_{solid} = \frac{-mg\theta_y}{\frac{\frac{2}{5}mR^2}{R^2}+m} \qquad \text{Eq. 4.32}$$

after some mathematical calculations

$$X_{solid} = -\frac{5}{7}g\theta_y \qquad \text{Eq. 4.33}$$

And for y

$$Y_{solid} = \frac{-mg\theta_x}{\frac{\frac{2}{5}mR^2}{R^2}+m} \qquad \text{Eq. 4.34}$$

so

$$Y_{solid} = -\frac{5}{7}g\theta_x \qquad \text{Eq. 4.35}$$

The Equations (4.33) and (4.35) will consider as the transfer function for ball and plate system in both directions x and y respectively.

## System Transfer Function

We already found the transfer function of the ball and plate and servo motor systems so the transfer function for the entire system will be the combined of the two systems.

$$G_{x,y}(s) = \frac{K_t K_g g}{\frac{5}{7}s^3[(Js+b)(L_a s+R_a)+K_b K_t} \qquad \text{Eq. 4.36}$$

## PID Controller Design

To simplify our design, we will create a system with two feedback loops. The first, which is the inner loop, will regulate the motor's angle, while the second, which is the outer loop, will utilize the inner loop to control the ball's location. The inner loop has two loops, one of which controls servo movement in the x direction and the other in the y direction. The output of these two loops will be sent to the ball and plate system, which will subsequently be routed to the outer loop, which will regulate the position (Taifour, A. Almahdi, H. Et al. (2017), Ogata, K. (1970)).

Figure 6 depicts the control diagram of our system.

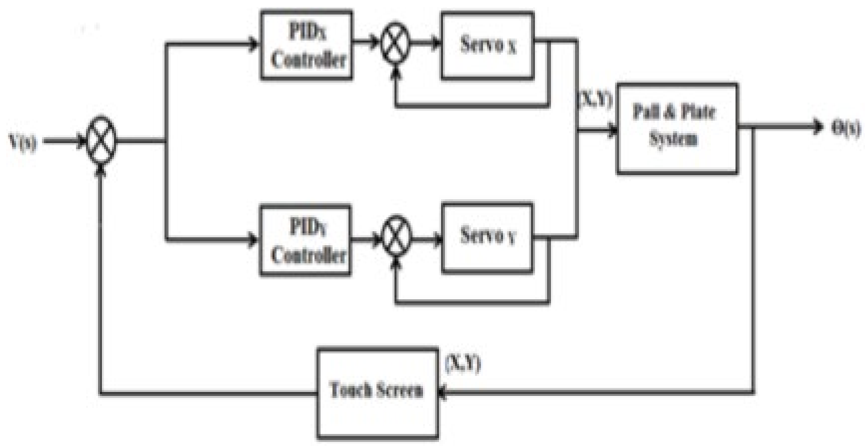


Figure 6. The implemented PID controller design in proposed system

The following Figure 7 demonstrates is the final schematic diagram of the electrical circuit.

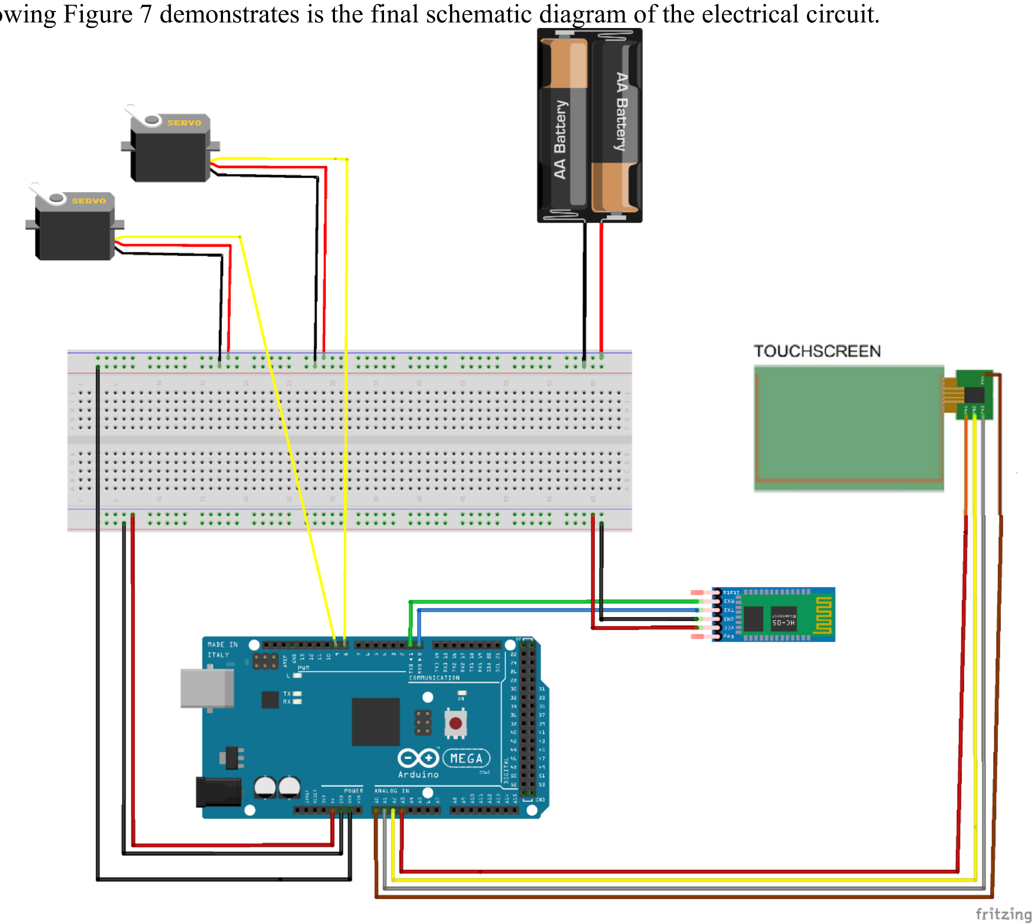


Figure 7: Final schematic diagram

**Program Flowchart**
The overall flowchart of the system is shown in Figure 8.

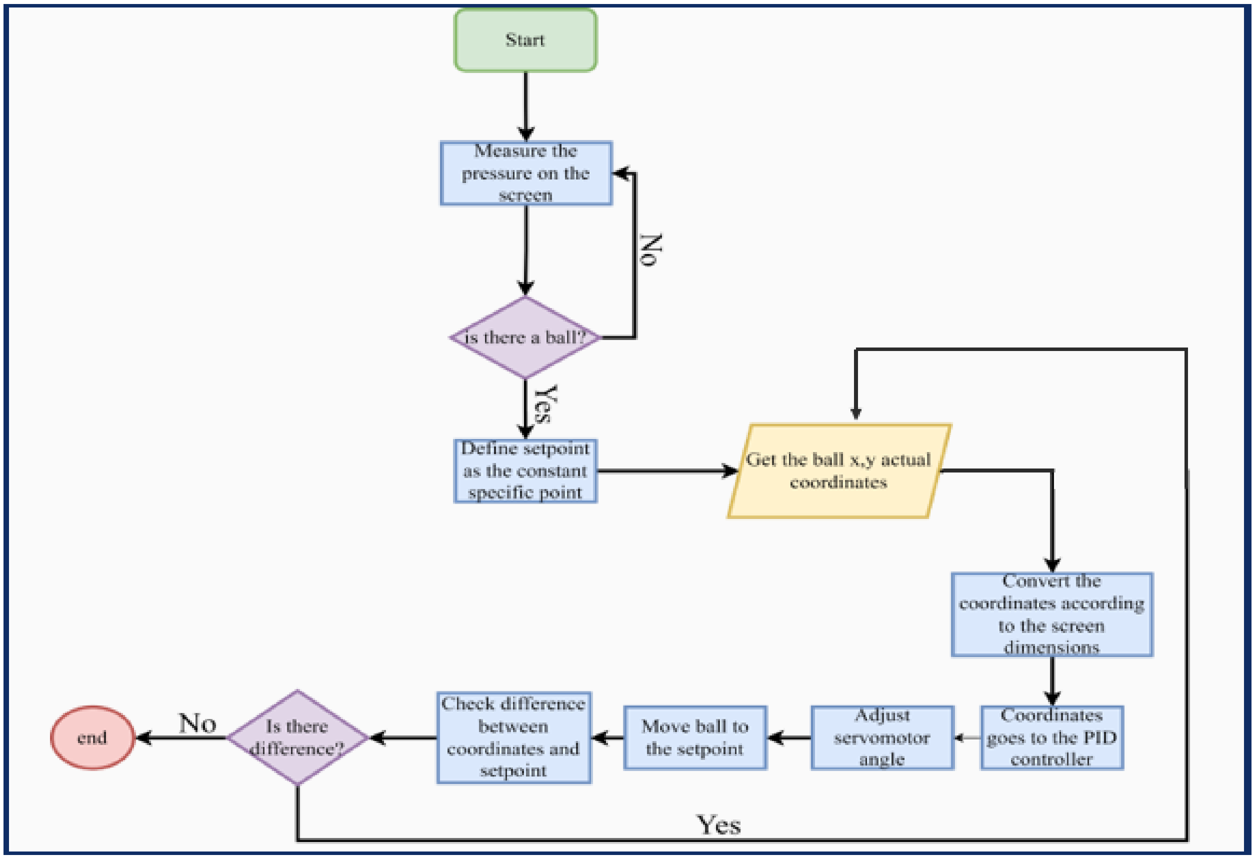


Figure 8. The proposed system flowchart

## 3.2 Graphical Results

### System Design

In this chapter, we present an overview simulation that have been done before the implementation of the prototype and hardware.

By utilizing MATLAB Simulink to simulate the behaviour of our system. Initially, we performed simulations without incorporating the Particle Swarm Optimization (PSO) technique, relying on manual tuning of the PID controller parameters. These simulations provided us with valuable insights into the system's response and allowed us to evaluate its performance under different conditions.

Subsequently, we integrated the PSO optimization technique into our simulations, aiming to optimize the parameters of the PID controller. The objective function used for the optimization process focused on minimizing the Integral Absolute Error (IAE) (which is illustrated in Equation 4.37) of the ball's position on the plate. By utilizing the PSO algorithm, we sought to enhance the overall performance and stability of our system.

$$IAE = \int |e(t)|dt \qquad \text{Eq. 4.37}$$

The results obtained from the simulations conducted both with and without the PSO optimization technique are presented in the following Figures 9-14. These step response graphs provide a visual representation of the system's behaviour and illustrate the impact of parameter tuning on the system's performance.

Comparing the two sets of results allows us to assess the effectiveness of the PSO optimization in improving the system's response and achieving the desired control objectives.

$$J = \min_{K_p, K_I, K_D} \int_0^\infty |e(t)| dt \quad \text{Eq. 4.38}$$

It is worth noting that these simulation results serve as an essential steppingstone towards the implementation and testing phase of our project. They provide us with valuable insights into the expected behaviour of the system and offer a foundation for further refinement and optimization.

## System Implementation and Specifications

The design was made in the MATLAB® R2022b, Windows 10 PC with 16GB of RAM, SSD, i7-10th CPU @3.90 GHz. The utilized motor parameters and ratings are shown in Table 1.

Table 1. Ball and plate system parameters

| Parameter | Value | Unit |
|---|---|---|
| Rated armature voltage | 230 | Volt |
| Rated armature current | 8.5 | Amp |
| Horsepower | 2 | Hp |
| Rated speed | 1500 | r.p.m |
| Armature Resistance $R_a$ | 2.45 | Ohm |
| Armature inductance $L_a$ | 0.035 | H |
| Frictional constant $B$ | $0.5 \times 10^{-3}$ | $N \times m/(rad/sec)$ |
| Back emf constant $K_b$ | 1.2 | $volt/(rad/sec)$ |
| Moment of inertia $J$ | 0.022 | $kg \times m^2/rad$ |

Therefore, the transfer function of the plant after substituting the aforementioned values is as follows:

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{6.8\times10^{-4}}{12\times10^{-9}s^3+3.9\times10^{-3}s^2+3.9\times10^{-3}s} \quad \text{Eq. 4.39}$$

## Simulation Results

This section presents a comprehensive analysis of the performance of our ball and plate system using MATLAB Simulink. We implemented our system based on the derived transfer function, as detailed in Chapter 3 and 4 of this report.

To ensure accuracy, we utilized the system specifications provided in a dedicated table (1). Through extensive simulations, we investigated the system's response under different control strategies and variations in the system parameters. By leveraging the capabilities of MATLAB Simulink, we obtained valuable insights into the behaviours of our system, enabling us to evaluate its stability, robustness, and overall performance.

Furthermore, we present and discuss the simulation results, aiming to validate the effectiveness of our design choices and contribute to the advancement of ball and plate systems.

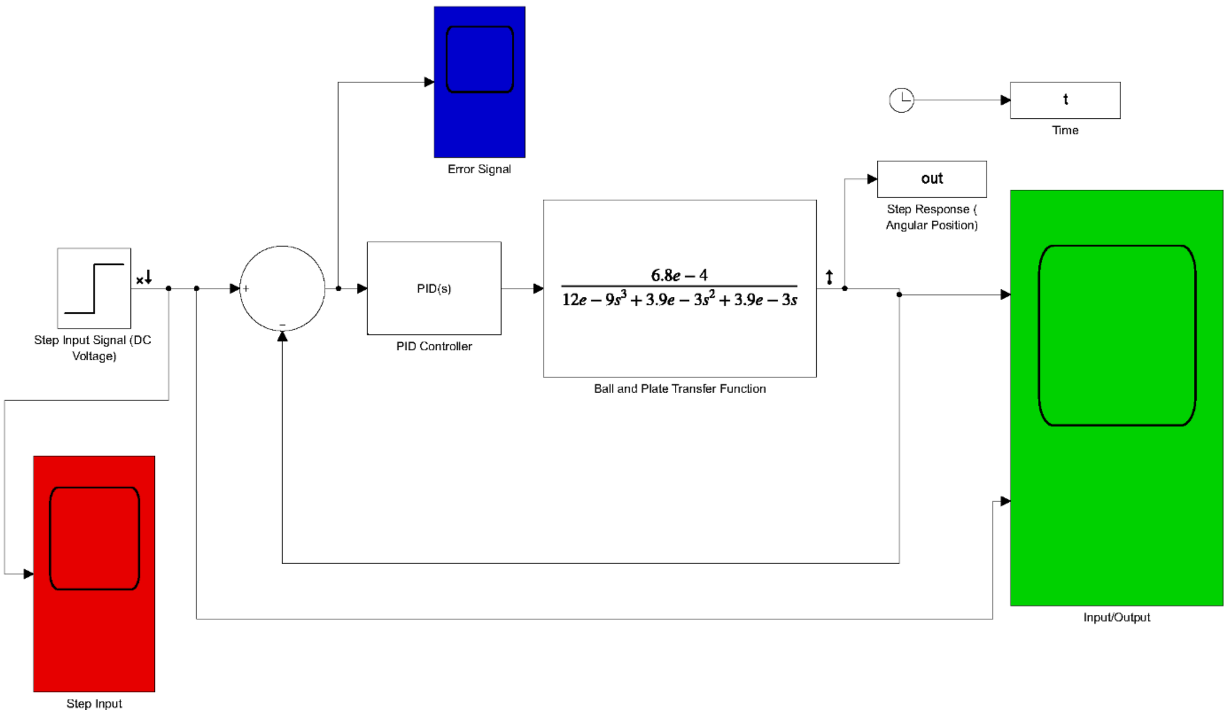


Figure 9. Original Simulink diagram

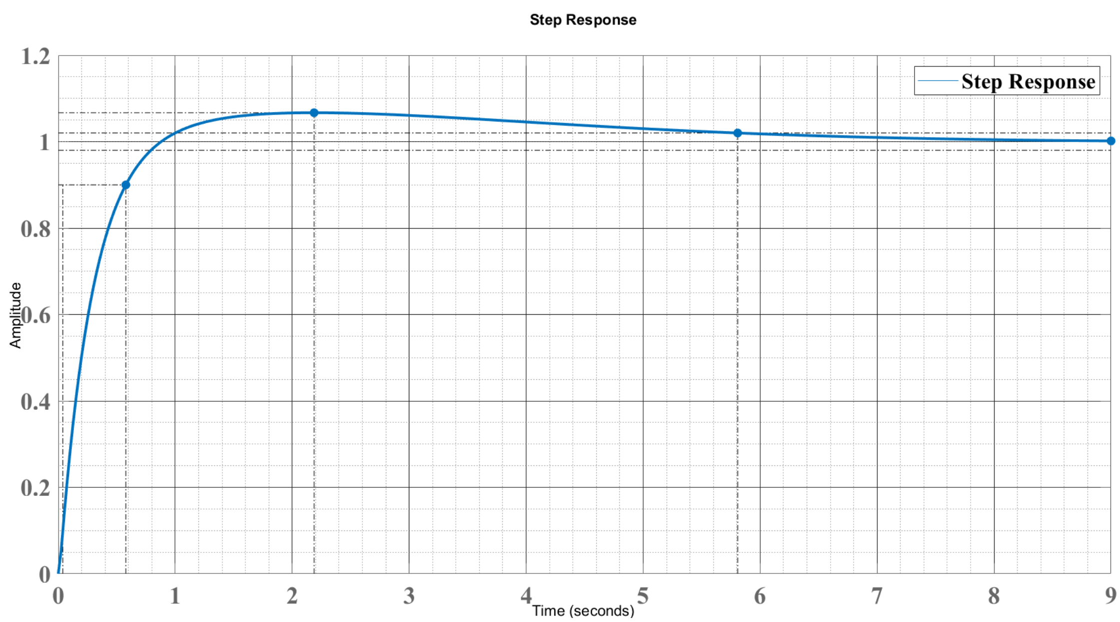


Figure 10. Step response characteristics using manual tuning

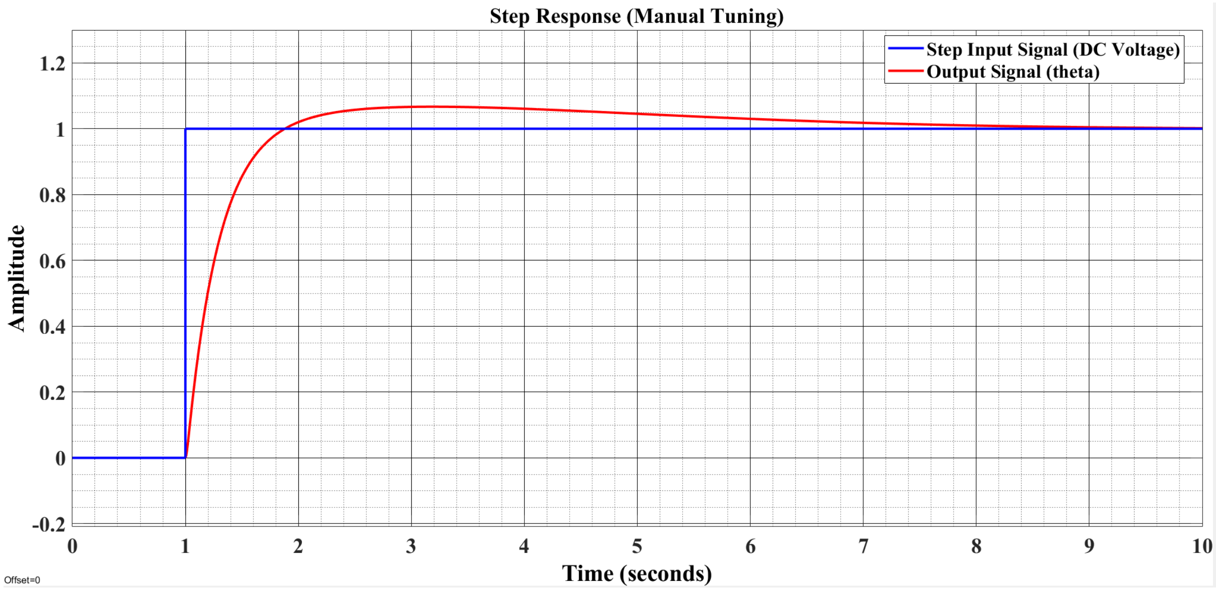


Figure 11. Input/output signals (step response with manual tuning)

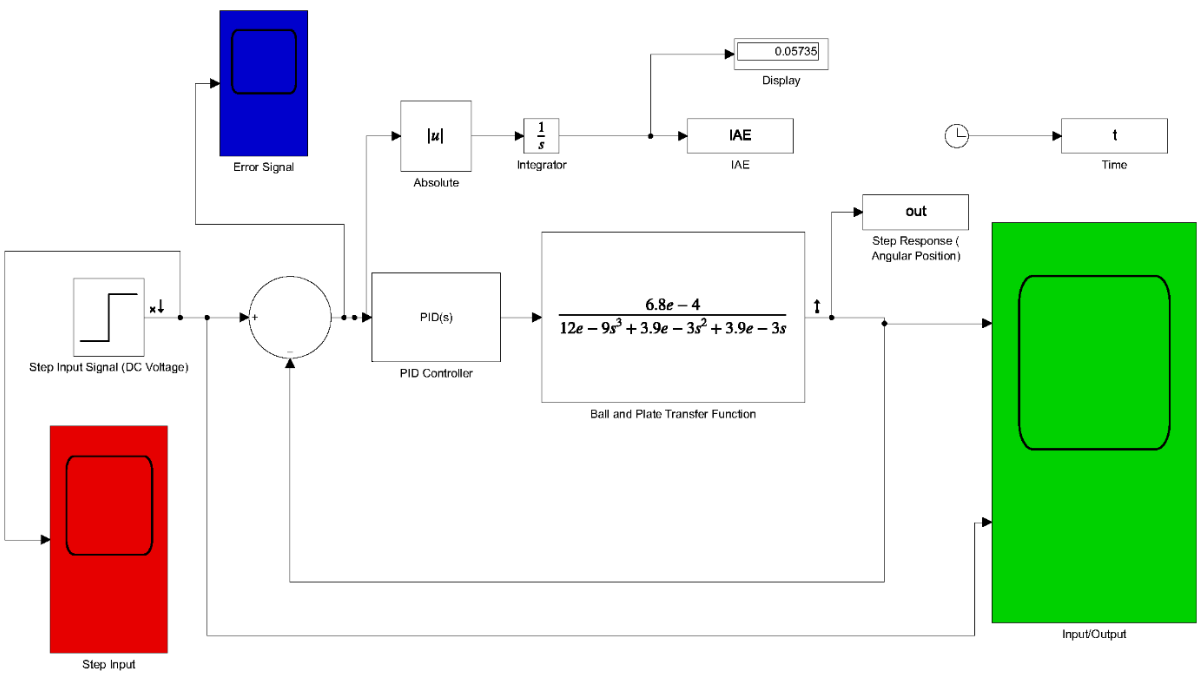


Figure 12. Simulink diagram with optimization

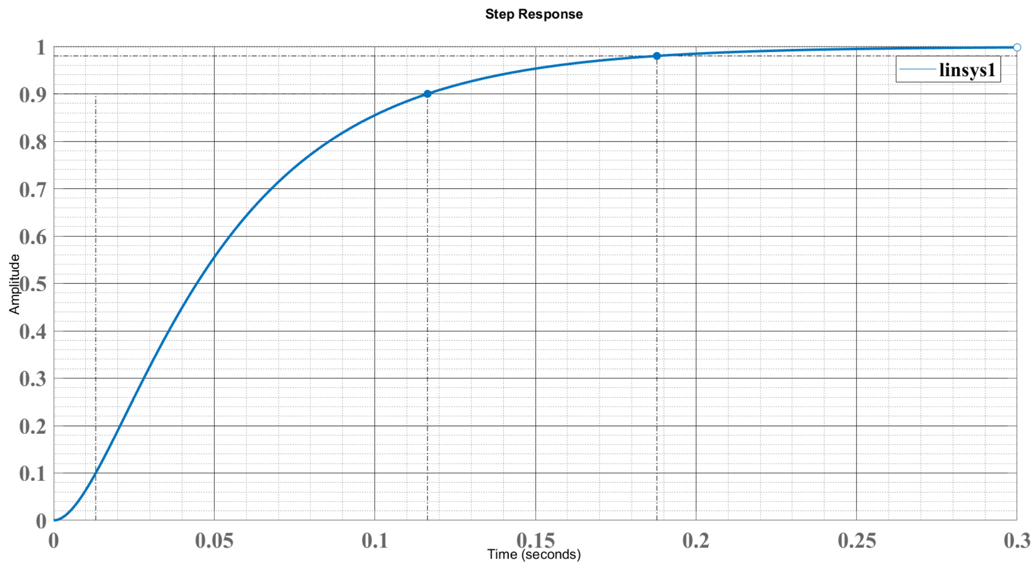


Figure 13. Step response characteristics using PSO optimization

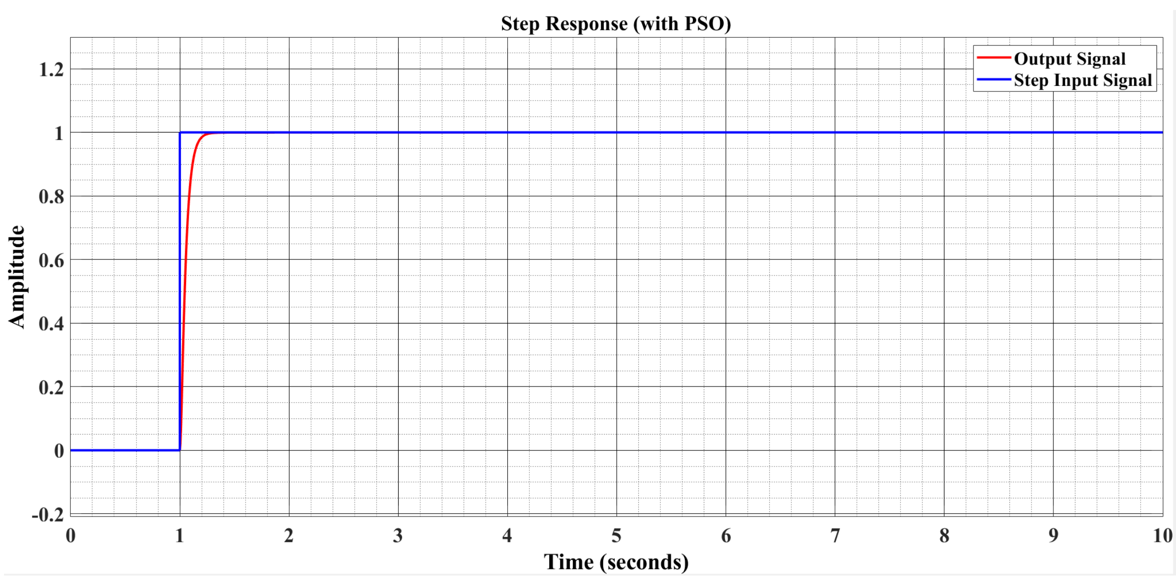


Figure 14. Input/output signals (step response with PSO optimization)

From the Figures (9-14), we can see that the PSO does highly enhanced the step response in the ball and plate system, where all step response characteristic values are enhanced and decreased (Rising time, settling time, overshoot). The following Table 2 depicts these parameters when tuning the PID controller manually, and when applying the PSO optimization technique Figures (15-17).

Table 2. Step response characteristics

| **Tuning Method** | **Step Response Specification** | | | |
|---|---|---|---|---|
| | $T_r$ | $T_s$ | $M_{o.s}\%$ | **IAE** |
| **PSO** | 0.1033 | 1.1878 | 0% | 0.05735 |
| **Manual Tuning** | 0.5387 | 6.8080 | 6.69 % | 0.5136 |

## Prototype Results

The following screenshots are illustrating the prototype and how it is installed.

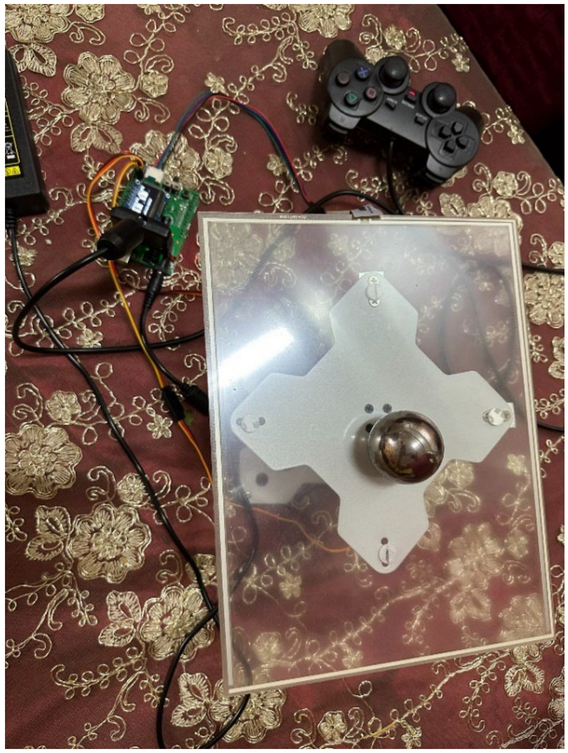

Figure 15: Final prototype screenshot 1

Figure 16: Final prototype screenshot 2

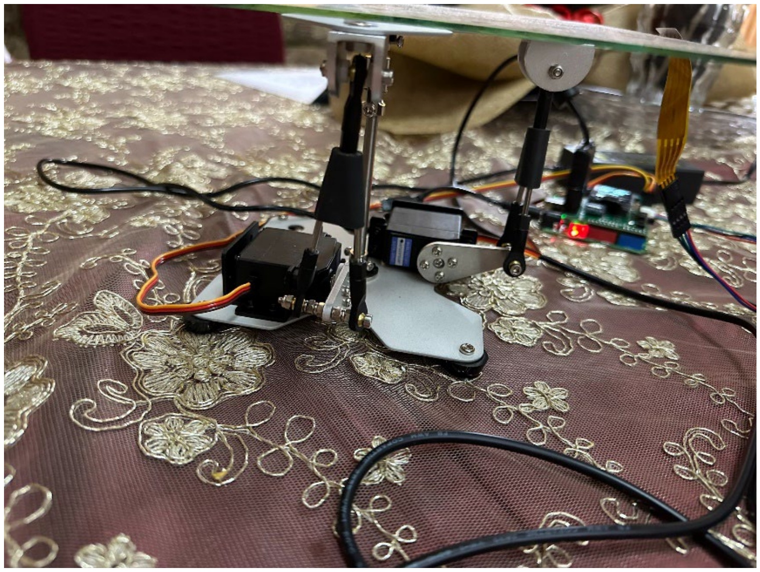

Figure 17: Final prototype screenshot 2

### 3.3 Proposed Improvements

In our project, we have identified several recommendations to enhance the performance and capabilities of the ball and plate system:

- Transitioning from a two-degree-of-freedom ($2DOF$) system to a six-degree-of-freedom ($6DOF$) system is advisable. By incorporating six degrees of freedom, we can achieve a faster response while maintaining the same level of quality. However, it is essential to note that this transition may introduce increased complexity in the system's design. Nevertheless, the benefits of improved speed and responsiveness make it a worthwhile consideration.
- We propose utilizing six servo motors instead of the current configuration to enhance stability and response time further. The system can achieve excellent stability and a faster response to disturbances by incorporating six servo motors. This increased actuation capability allows for finer control and adjustment of the platform, resulting in improved overall performance.
- Consider implementing more advanced control techniques such as fuzzy logic. Fuzzy logic control systems offer the ability to handle complex and uncertain environments, making them well-suited for applications like the ball and plate system. By employing fuzzy logic control; we can leverage its adaptive and robust nature to enhance the system's performance, particularly in scenarios involving varying operating conditions or external disturbances.

## 4. Conclusion

To sum up, we used the PSO algorithm into the simulations to improve the performance of our system. We intended to improve the system's stability and precision by setting the goal function as reducing the Integral Absolute Error (IAE) of the ball's position on the plate. The comparison of simulation results with and without PSO optimization offered useful insights into the optimization technique's efficacy and impact on the system's responsiveness.

In the conclusion, the primary objective of our ball and plate system is to precisely control the position of the ball on the touch screen, whether maintaining it in a static position or guiding it along predetermined paths, while promptly rectifying any disturbances that occur. The reference point can be set as the center of the plate or adjusted to a user-defined location. Regardless of the magnitude of the disturbance, the system swiftly restores the ball's position, ensuring minimal steady-state error, negligible overshoot, and rapid response time. Through the completion of this project, we have acquired substantial knowledge across various domains, underscoring its educational value, particularly in university laboratory settings. By incorporating this system, we can provide students with a deeper comprehension of control systems and their practical applications. The insights gained from this project have furthered our understanding and enabled us to contribute to the continuous advancement of control systems technology.

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## Biographies

**Abdullah Tahir** is a Sales Engineer at ALMASA Environmental Solutions, Sharjah, United Arab Emirates (UAE). Eng. Tahir completed the Bachelor's degree in Electrical Engineering, with concentration in Power and Energy, at the University of Dubai (UD). During his academic journey, he delved into the intricacies of electrical systems, with a particular focus on power and energy applications. His professional journey began with a valuable internship at Cummins Arabia, a leading multinational company. During his time there, he dedicated himself to refining the sales process, leveraging his skills to make a substantial impact. Through the development and implementation of innovative tools, he successfully enhanced the company's sales process by an impressive 80%. This achievement did not go unnoticed, as his efforts were appreciated by the Managing Director of Cummins, underscoring the effectiveness of his contributions to the organization. Eng. Tahir is enthusiastic about applying his knowledge and skills gained from both academic and professional experiences to contribute meaningfully to future endeavors. His passion for electrical engineering, coupled with a proven track record of driving positive change, motivates him to pursue new challenges and opportunities in the field.

**Maisam Wahbah** is an Assistant Professor at the College of Engineering and Information Technology at the University of Dubai, Dubai, United Arab Emirates (UAE). She received the B.Sc., M.Sc. and Ph.D. degrees in Electrical and Computer Engineering from Khalifa University, Abu Dhabi, UAE. Her M.Sc. research project focused on designing an efficient power conversion circuit for the piezo electric energy harvester as part of a fully autonomous biomedical system. During her Ph.D. research, she focused on renewable energy characterization for optimal energy utilization. Dr. Wahbah joined the Department of Biomedical Engineering at Khalifa University as a Post-Doctoral Fellow from 2019 to 2022. In her research work, she analyzed the interaction between the pregnant mother and the fetus by using ECG signals recorded from human as well as mice subjects. She is currently the IEEE UAE Section Awards and Recognition Committee Chair. Her research interests include signal processing, biomedical data analysis, nonparametric statistical modeling, and circuits and systems.

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