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RESEARCH ARTICLE

A Comparative Analysis of Intelligent Control Approaches for the Ball-and-Plate Problem

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ABSTRACT - This paper conducts a comprehensive comparative analysis of five intelligent control approaches applied to the Ball-and-Plate problem, evaluating their performance based on Step Response metrics and Trajectory Tracking Mean Absolute Error (MAE). The techniques examined include Proportional-Integral-Derivative (PID), Linear Quadratic Regulation (LQR), Model Predictive Control (MPC), Sliding Mode Control (SMC), and Fuzzy Logic Control (FLC). Through rigorous experimentation and analysis, each technique's strengths and weaknesses are identified, with MPC and SMC emerging as superior options in terms of response time and trajectory tracking accuracy, notably achieving zero overshoot and minimal errors. LQR exhibits exceptionally fast response times, while PID and FLC offer moderate performance. The study's findings provide valuable insights for selecting appropriate control techniques tailored to specific application requirements and suggest avenues for future research, including the exploration of hybrid control approaches and adaptive control algorithms to enhance system robustness and reliability in addressing the Ball-and-Plate problem.

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1.0 INTRODUCTION

The Ball-and-Plate system is a benchmark control system in the field of control engineering, offering a dynamic and challenging environment for testing and developing control algorithms [1, 2]. Characterized by its simplicity yet rich dynamics, this system has been extensively studied over the years, serving as a playground for exploring various control methodologies [3]. This system, consisting of a tiltable plate upon which a ball can move freely, presents inherent nonlinearities, coupled dynamics, and uncertainties, making it an ideal testbed for evaluating the efficacy of intelligent control methodologies [4].

Over the years, researchers have explored a myriad of intelligent control approaches to tackle this problem, aiming to achieve robust and efficient performance. Early studies primarily focused on conventional control techniques such as Proportional-Integral-Derivative control [5–10]. These methods laid the foundation for further research by demonstrating basic control principles and establishing performance benchmarks against which more advanced techniques could be compared.

With the advent of intelligent control paradigms, the focus shifted towards incorporating machine learning and artificial intelligence (AI) algorithms for addressing the ball and plate problem [11, 12]. One prominent approach involved the utilization of neural networks for modelling the nonlinear dynamics of the system and designing adaptive control schemes [13]. These studies showcased the potential of neural network-based controllers in achieving superior tracking accuracy as well as disturbance rejection compared to traditional methods. However, challenges related to network training, generalization, and computational complexity remained significant hurdles in practical implementations.

In addition to intelligent control approaches, optimal and robust control methods have also been explored in the context of the ball and plate problem. Optimal control techniques, such as Linear Quadratic Regulator (LQR) [14] and Model Predictive Control (MPC) [15], aim to minimize a predefined cost function while satisfying system constraints. These methods offer rigorous mathematical frameworks for designing controllers that can achieve desired performance criteria, such as minimizing settling time or energy consumption. Robust control methodologies, on the other hand, focus on ensuring stability and performance despite uncertainties and variations in system parameters. Techniques like H-infinity control [16–18] and μ-synthesis [19] are particularly well-suited for addressing modelling errors, disturbances, and external perturbations in the ball and plate system. By integrating optimal and robust control strategies, researchers seek to develop controllers that not only optimize performance under nominal conditions but also maintain stability and robustness in the face of uncertainties, thus enhancing the reliability and effectiveness of the control system for real-world applications.

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In recent years, the integration of evolutionary algorithms such as genetic algorithms [20, 21] and particle swarm optimization [22–24] has emerged as a promising direction in the quest for optimal control solutions for the ball and plate system. These approaches offer advantages in terms of global optimization and robustness to uncertainties, thereby addressing some of the limitations associated with gradient based optimization methods. Moreover, hybrid approaches combining neural networks with evolutionary algorithms have been proposed to harness the strengths of both paradigms, leading to enhanced control performance and adaptability.

Presently, the field of intelligent control for the ball and plate problem continues to evolve rapidly, fuelled by advancements in computational techniques, machine learning, and optimization algorithms. Future research directions may include the exploration of reinforcement learning-based approaches [3, 25], decentralized control strategies [26], and real-time implementation considerations [27]. By building upon the rich legacy of previous studies and leveraging the latest developments in control theory and AI, researchers aim to develop robust, efficient, and scalable solutions for addressing the challenges posed by the ball and plate system in various practical applications.

Looking ahead, recent advancements in the field have seen a shift towards hybrid intelligent control approaches that combine multiple techniques to leverage their respective strengths. Hybrid control schemes, integrating elements of fuzzy logic, neural networks, and evolutionary algorithms, have demonstrated remarkable performance improvements in terms of stability, tracking accuracy, and disturbance rejection. By synergistically combining different intelligent control paradigms, researchers aim to further enhance the control capabilities of the ball and plate system, paving the way for applications in areas such as robotics, automation, and motion control.

This paper presents a comprehensive comparative analysis of various intelligent control approaches applied to the ball-and-plate problem. By examining and evaluating the effectiveness of different techniques, including but not limited to neural networks, fuzzy logic systems, evolutionary algorithms, and reinforcement learning methods, this study aims to provide insights into the strengths, weaknesses, and applicability of each approach in tackling the challenges posed by the ball-and-plate system.

Through rigorous experimentation and performance evaluation, this research endeavours to shed light on the relative merits of different intelligent control strategies, offering valuable guidance for researchers and practitioners in selecting the most suitable approach for their specific application requirements. Ultimately, the findings of this study contribute to advancing the state-of-the-art in intelligent control methodologies for complex dynamic systems, paving the way for improved performance and reliability in various real-world applications.

1.1 Contribution

The contribution of the paper lies in its comprehensive comparative analysis of various intelligent control approaches for the ball and plate problem. By systematically evaluating and contrasting different methodologies, including classical control techniques, fuzzy logic control, neural network-based control, and hybrid intelligent control schemes, the paper provides valuable insights into the strengths and limitations of each approach. This comparative study facilitates a deeper understanding of the underlying principles and mechanisms governing the control of the ball and plate system, thereby guiding researchers and practitioners in selecting the most suitable control strategy for specific application requirements.

The rest of this paper is ordered as follows: In section 2, the mathematical model of the Ball-and-Plate system is given. Section 3 gives the design and integration of the various controllers while section 4 presents a comparison on the results obtained. Finally, in section 5, a conclusion and recommendation for future works is given

2.0 MATHEMATICAL MODELLING

In order to obtain the mathematical description of the Ball-and-Plate system, the system is first decomposed along the x and y axis into two sub-components according to [28]. This decomposition is illustrated in Figure 1

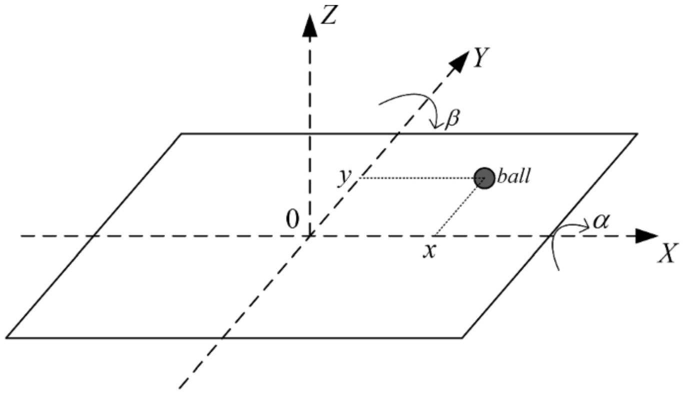


Figure 1: A pictorial illustration of a Ball-and-Plate System

The mathematical equations representing the system's dynamics can be formulated using the Euler-Lagrange equation given in equation 1

$$Q_i = \frac{d}{dt}\left[\frac{\partial E}{\partial \dot{q}_i}\right] - \frac{\partial E}{\partial q_i} + \frac{\partial P}{\partial q_i} \tag{1}$$

This equation describes the dynamics of a system by relating the system's energy E, its generalized coordinates q_i their rates of change $\dot{q}_i$ and the generalized forces Q_i acting on the system. Accordingly, [29] derived the nonlinear dynamic equations governing the ball positioning along the x and y axis as follows:

$$x; \left(m_b + \frac{I_b}{r_b^2}\right)\ddot{x_b} - m_b(x_b\dot{\alpha}^2 + y_b\dot{\alpha}\beta) + m_b g sin\alpha = 0 \tag{2}$$

$$y; \left(m_b + \frac{I_b}{r_b^2}\right)\ddot{y_b} - m_b\left(y_b\dot{\beta}^2 + x_b\dot{\alpha}\beta\right) + m_b g sin\beta = 0 \tag{3}$$

These equations can be linearized around an operating point by making the following assumptions about the operation of the system [29, 30].

1. The maximum tilt angle of the plate is less than $\pm 5^0$ therefore $sin\alpha \approx \alpha$.
2. The time rate of change of the plate's tilt angle is negligible therefore $\dot{\alpha}^2 \approx 0$
3. A spherical ball's moment of inertia can be approximated as$I_b = 2/5 m_b r_b^2$, where m_b and r_b accounts for the ball's mass and radius respectively.

The following linear differential equation can be obtained by subsisting the above assumptions into equation 2. For the purpose of this study, equation 3 is neglected due to the symmetrical nature of the system.

$$\frac{7}{5}\ddot{x_b} + g \times \alpha = 0 \tag{4}$$

A transfer function representing the plate's inclination angle to the ball position can now be obtained by taking a Laplace transformation of equation 4. This results in the classical system representation given in equation 5

$$\frac{x_v(s)}{\alpha(s)} = \frac{y_b(s)}{\beta(s)} = -\frac{5g}{7s^2} \tag{5}$$

The following first-order transfer function can be used a reliable and approximate representation of the workings of a servo motor [29]

$$G_m(s) = \frac{K_m}{T_m(s) + 1} \tag{6}$$

When Km = −0.6864 and Tm = 0.187, the resulting plant system model according to [3, 29] can be represented as:

$$G_p(s) = -\frac{0.6854}{0.187s + 1} \times -\frac{5g}{7s^2} = \frac{4.803}{0.187s^3 + s^2} \tag{7}$$

Consequently, the state space model of the system can be derived from this transfer function as:

$$\dot{x} = Ax + Bu \tag{8}$$

$$y = Cx + DU \tag{9}$$

Where:

$$A = \begin{pmatrix} -5.3476 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \tag{10}$$

$$B = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \tag{11}$$

$$C = \begin{pmatrix} 0 & 0 & 25.6845 \end{pmatrix} \tag{12}$$

$$D = 0 \tag{13}$$

3.0 CONTROLLER DESIGN

In this section five methods of controlling the ball positioning on the plate are proposed. These methods are analysed based on the transient and steady state responses of the overall system when excited by a step input signal. Additionally, the trajectory tracking performance of the various controllers will be analyzed based mean absolute errors when trailing a circular path.

3.1 Proportional Integral Derivative Control

A Proportional Integral Derivative (PID) controller is a widely used feedback control mechanism employed in various engineering applications, including robotics and automation systems. The PID controller operates by continuously calculating an error signal, which is the difference between a desired setpoint and the measured process variable. The controller then adjusts the system's output based on three components: proportional, integral, and derivative terms in accordance with equation 14.

$$u(t) = K_p \times e(t) + K_i \int_0^\infty e(t) + K_d \frac{d}{dt} e(t) \tag{14}$$

The proportional term contributes to the output proportionally to the current error magnitude, aiming to minimize steady-state error. The integral term integrates the error over time, addressing any accumulated error and eliminating steady-state offsets. Meanwhile, the derivative term considers the rate of change of the error signal, providing damping to prevent overshoot and improve system stability. The layout of the PID controller connected to the Ball-and-Plate system is given in Figure 2

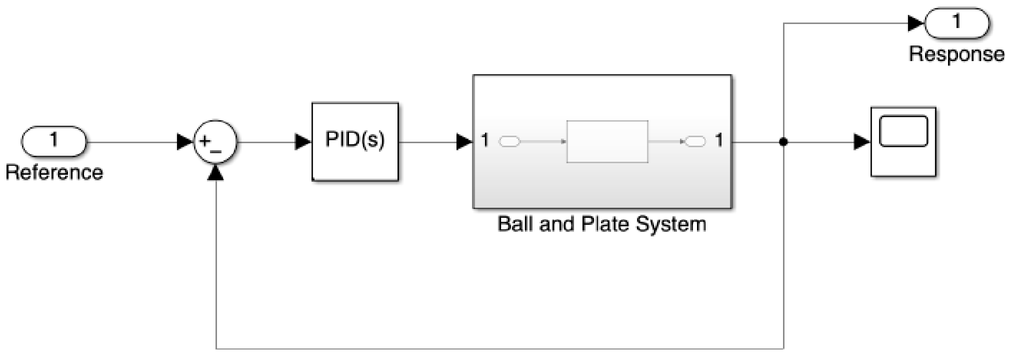
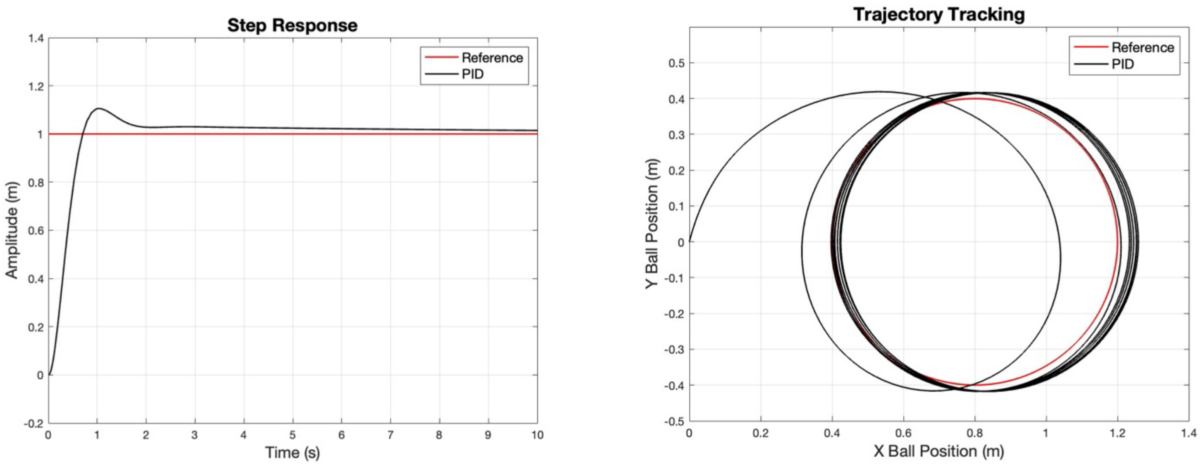


Figure 2. PID controller integrated with the Ball-and-Plate System

The PID controller for stabilizing the ball positioning was tuned using the transfer function method of MATLAB's inbuilt PID tuner with a response time of 0.7290 seconds and transient behaviour of 0.600 seconds. The proportional, integral and derivative gains were obtained as follows: $K_p = 0.071913824221689$, $K_i = 0.0013566713809414 5$, and $K_d = 0.641396703623824$. The step response of the overall system integrated with the PID controller is given in Figure 3a while the circular trajectory tracking performance is demonstrated in 3b



(a) Step response plot (b) Trajectory tracking plot

Figure 3. Performance of the PID controller when integrated with the Ball-and-Plate system illustrated by step response and trajectory tracking plots

The quantitative performance of the system can also be obtained as: $t_r = 0.4812$ seconds, $t_s = 1.7612$ seconds, $M_p = 8.9739\%$, and MAE = 0.4262. Additionally, the trajectory tracking error is obtained as MAE = 0.1149

3.2 Model Predictive Control

Model Predictive Control (MPC) is a control method that uses a dynamic model to predict future system behavior and determine optimal control actions over a defined time horizon. Unlike traditional controllers that compute feedback based on current states, MPC considers future states and system dynamics, enabling it to handle constraints and anticipate future disturbances. The MPC algorithm formulates an optimization problem where the objective is typically to minimize a cost function (J_{mpc}), which incorporates control objectives such as setpoint tracking, disturbance rejection, and constraint satisfaction.

$$J_{mpc} = \sum_{i=1}^{p} \left(r_{k+j} - y_{k+j}^{c-}\right)^2 + w \sum_{i=1}^{m-1} \Delta u_{k+1}^2 \tag{15}$$

Given that:

$$r_{k+j} - y_{k+j}^{c-} = r_{k+j} - \sum_{i=1}^{n-1} S_i \Delta u_{k-i+j} + S_n \, \Delta u_{k-n+j} + d_{k+j} - \sum_{i=1}^{j} S_i \Delta u_{k-i+j} \tag{16}$$

Where r_{k+j} is the reference signal and the y_{k+j}^{c-} is the manipulated signal, the variable w accounts for the weights and u_{k+1} describes the control input for a time step k. The variables $S_i \dots S_n$ accounts for the model coefficients. By solving this optimization problem iteratively at each time step, MPC generates control signals that steer the system towards optimal performance while satisfying constraints.

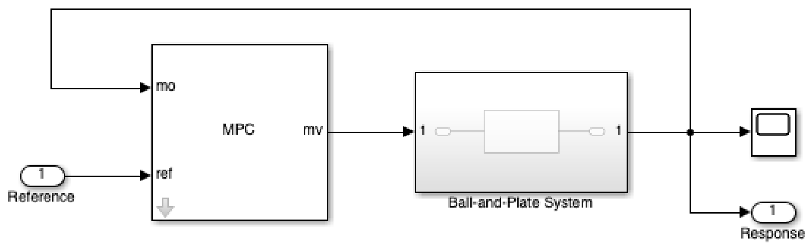
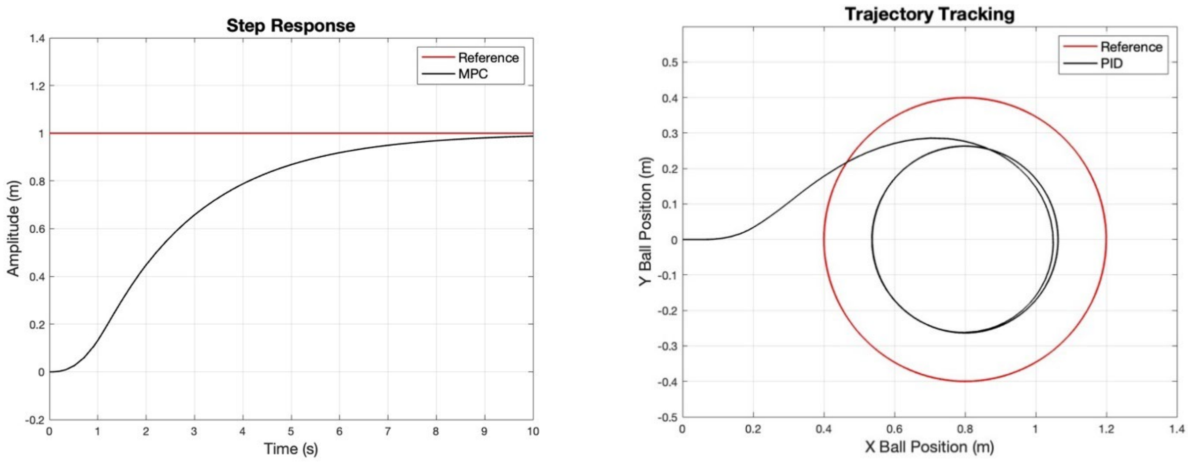


Figure 4. MPC controllers integrated with the Ball-and-Plate System

In the context of the Ball-and-Plate problem, MPC could provide robust and adaptive control by continuously predicting the ball’s trajectory and optimizing control actions to maintain stability and achieve desired performance objectives despite uncertainties and external disturbances. The overall layout the MPC controller integrated to the Ball-and-Plate system is shown in Figure 4 while the step response trajectory tracking plots are given in Figure 5a and 5b respectively.



(a) Step response plot (b) Trajectory tracking plot

Figure 5. Performance of the MPC controller when integrated with the Ball-and-Plate system illustrated by step response and trajectory tracking plots

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The quantitative performance of the system can also be obtained as: $t_r = 0.8485$ seconds, $t_s = 0.9867$ seconds, $M_p = 0.0000\%$, and $MAE = 0.3675$. Additionally, the trajectory tracking error is obtained as $MAE = 0.5845$

3.3 Sliding Mode Control

A Sliding Mode Controller (SMC) is a robust control technique renowned for its ability to ensure system stability and performance in the presence of uncertainties and disturbances. At the core of SMC is the concept of a sliding surface, a hyperplane in the state space along which the system dynamics are constrained to evolve. The controller's objective is to drive the system states onto this sliding surface and keep them there. Once on the sliding surface, the system dynamics are governed by a simple and robust control law designed to maintain the system's motion along this surface, effectively decoupling the system from uncertainties and disturbances. The sliding surface s is typically designed as the error between the desired state x_d and the actual state x.

$$s = x_d - x \tag{17}$$

The control law is often discontinuous and designed to drive the system trajectory onto the sliding surface. A common choice for the control law is:

$$u = -k sign(s) \tag{18}$$

The distinctive feature of SMC lies in its ability to achieve robustness against parameter variations and external disturbances by enforcing a sliding motion, making it particularly suitable for systems with nonlinear dynamics and uncertainties

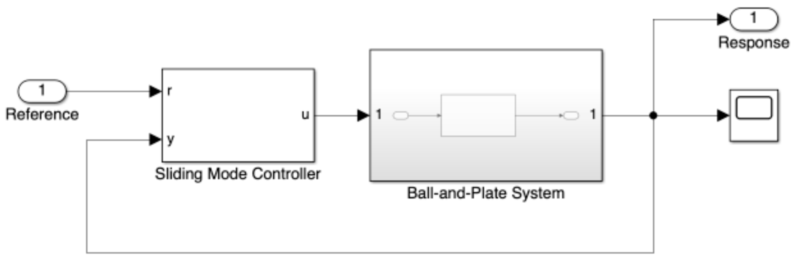
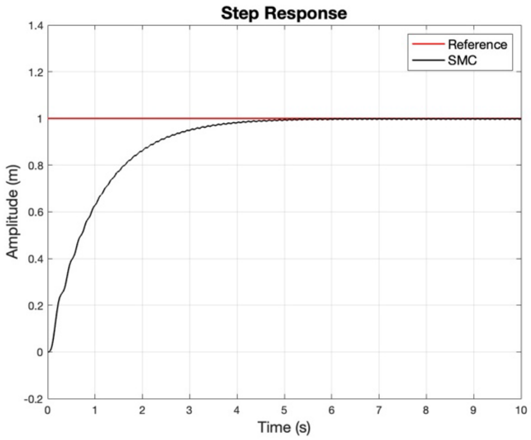
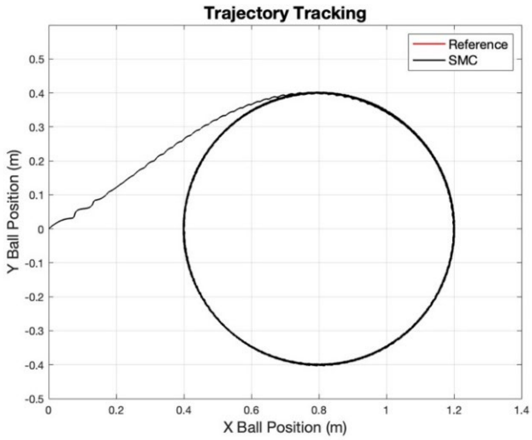


Figure 6. SMC controller integrated with the Ball-and-Plate System

In the context of the Ball-and-Plate problem, a Sliding Mode Controller could offer precise and robust control, ensuring that the ball's position on the plate remains stable and resilient to disturbances, even in the presence of uncertainties in the system dynamics or external forces acting on the ball. The overall layout the SMC controller integrated to the Ball-and-Plate system is shown in Figure 6 while the step response trajectory tracking plots are given in Figure 7a and 7b respectively



(a) Step response plot



(b) Trajectory tracking plot

Figure 7. Performance of the SMC controller when integrated with the Ball-and-Plate system illustrated by step response and trajectory tracking plots

The quantitative performance of the system can also be obtained as: $t_r = 0.3701$ seconds, $t_s = 0.9997$ seconds, $M_p = 0.0000$, and $MAE = 0.1024$. Additionally, the trajectory tracking error is obtained as $MAE = 0.0061$

3.4 Linear Quadratic Regulator

Linear Quadratic Regulator (LQR) control is a method used to design controllers for linear systems, aiming to minimize a quadratic cost function representing the system's performance and control effort. It operates by computing a control law that minimizes the expected value of the cost function J over a finite time horizon, taking into account both the current state and future state predictions. The LQR controller leverages a state feedback approach, where the control input is a linear function of the state variables.

$$J = \int_0^\infty (x^T Q x + U^T R u) dt \tag{19}$$

We chose Q, R matrices as follows:

$$Q = \begin{pmatrix} 0.3 & 0 & 0 \\ 0 & 0 & 0.21 \\ 0 & 0 & 0.1 \end{pmatrix} \tag{20}$$

$$R = 0.00015 \tag{21}$$

By solving the associated Riccati equation, the LQR algorithm determines the optimal feedback gain matrix that minimizes the cost function, thus enabling precise and efficient control.

$$K = (40.8079 \quad 61.2896 \quad 25.6850) \tag{22}$$

LQR is particularly effective for systems with known dynamics and noise characteristics, providing optimal control solutions that balance between tracking desired setpoints and minimizing control effort.

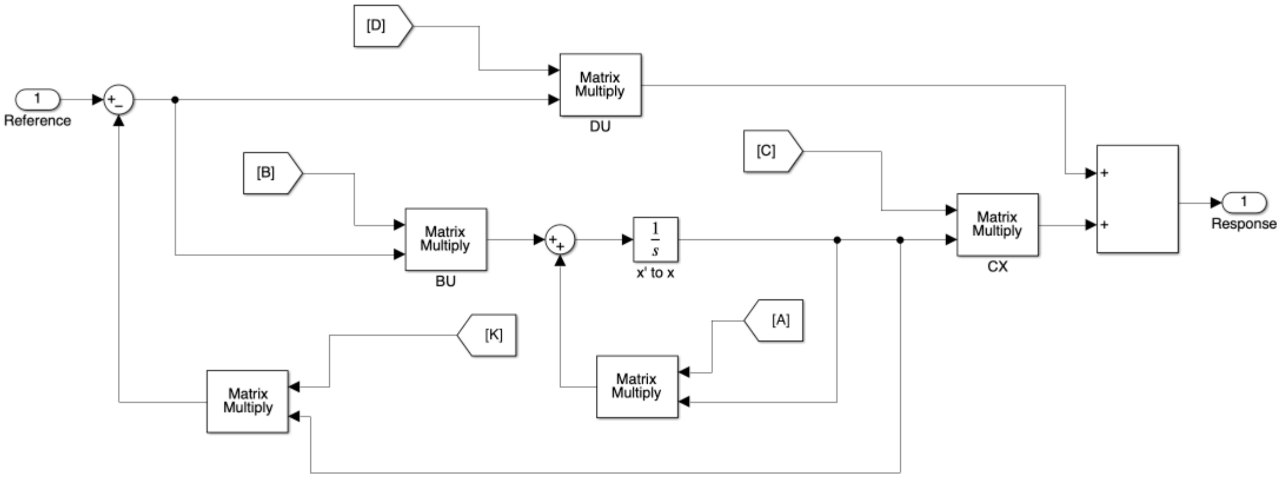
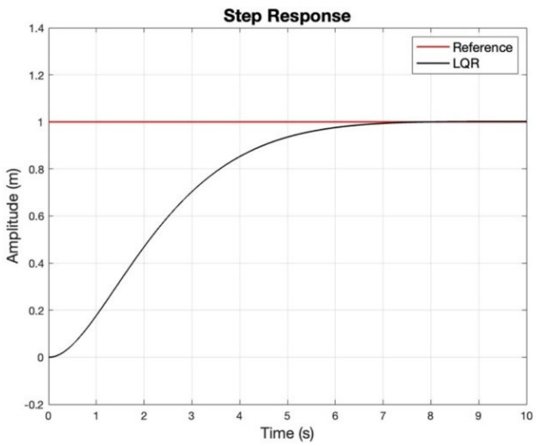
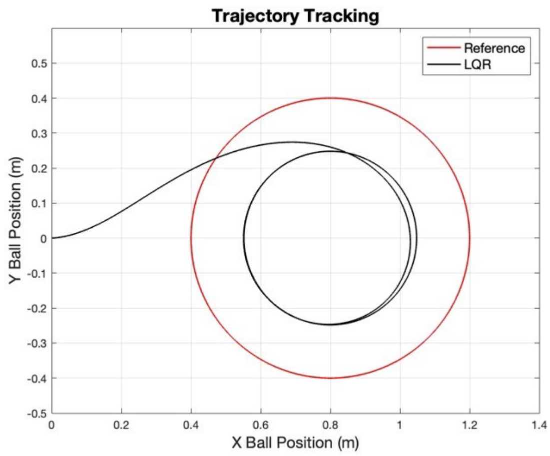


Figure 8. LQR controller integrated with the Ball-and-Plate System

In applications such as the Ball-and-Plate problem, where the dynamics can be approximated as linear and uncertainties are relatively low, an LQR controller could offer stable and accurate control to maintain the ball's position on the plate while minimizing deviations from the desired trajectory. The overall layout the LQR controller integrated to the Ball-and-Plate system is shown in Figure 8 while the step response trajectory tracking plots are given in Figure 9a and 9b respectively



(a) Step response plot



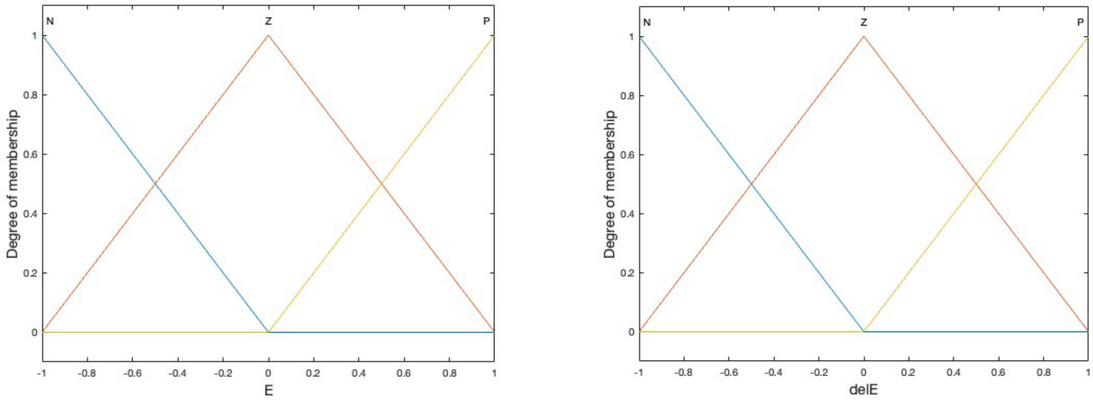
(b) Trajectory tracking plot

Figure 9. Performance of the LQR controller when integrated with the Ball-and-Plate system illustrated by step response and trajectory tracking plots

The quantitative performance of the system can also be obtained as: $t_r = 0.0017$ seconds, $t_s = 1.0000$ seconds, $M_p = 0.0000\%$, and $MAE = 0.0310$. Additionally, the trajectory tracking error is obtained as $MAE = 0.5140$

3.4 Fuzzy Logic Control

Fuzzy Logic Control (FLC) is a powerful control methodology that emulates human decision-making processes by incorporating linguistic variables and fuzzy rules to handle complex and uncertain systems. Unlike traditional control methods that rely on precise mathematical models, FLC operates on a set of linguistic rules and fuzzy membership functions shown in Figure 10 to map input variables to output actions.



(a) Input 1 (b) Input 2

Figure 10. Triangular membership functions for the two inputs

These rules capture the expert knowledge or heuristics about the system's behaviour, allowing for intuitive and interpretable control strategies. Fuzzy Logic Controllers excel in systems where precise mathematical modelling is challenging or impractical, such as those with nonlinearities, uncertainties, or vague input-output relationships. By leveraging fuzzy logic, FLC can effectively handle imprecise information and adaptively adjust control actions to suit changing operating conditions, making it suitable for a wide range of applications, including automotive control systems, industrial processes, and consumer electronics.

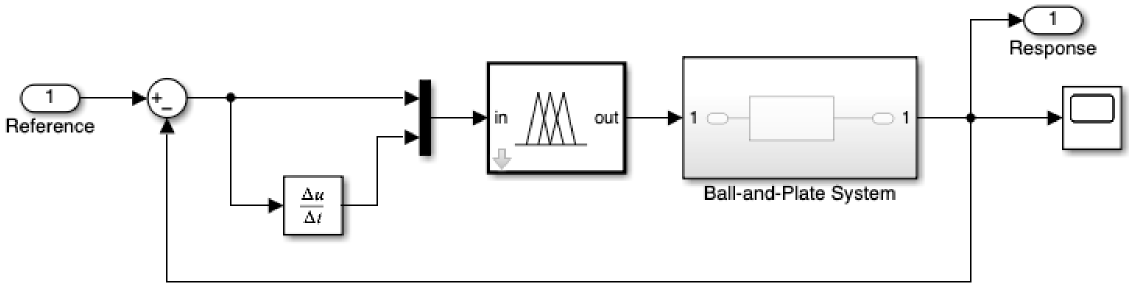
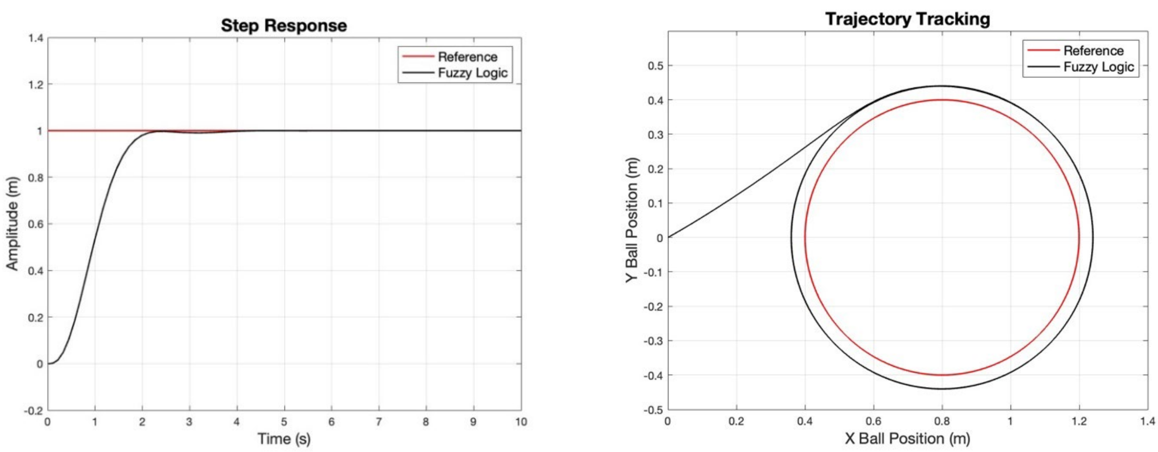


Figure 11. FLC controller integrated with the Ball-and-Plate System

In the context of the Ball-and-Plate problem, Fuzzy Logic Control could offer robust and adaptive control to stabilize the ball's position on the plate, even in the presence of uncertainties in the system dynamics or variations in external conditions. The overall layout the SMC controller integrated to the Ball-and-Plate system is shown in Figure 11 while the step response trajectory tracking plots are given in Figure 12a and 12b respectively.



(a) Step response plot (b) Trajectory tracking plot

Figure 12. Performance of the FLC controller when integrated with the Ball-and-Plate system illustrated by step response and trajectory tracking plots

The quantitative performance of the system can also be obtained as: $t_r = 0.4634$, $t_s = 0.9999$, $M_p = 0.0000$, and $MAE = 0.2181$. Additionally, the trajectory tracking error is obtained as $MAE = 0.0523$

4.0 RESULT ANALYSIS

Table 1 presents a comparative analysis of various intelligent control approaches for addressing the Ball-and-Plate problem, focusing on both step response and trajectory tracking performance metrics.

Table 1. Comparison of the 5 control methods investigated on the Ball-and-Plate system

Techniques	Step Response				Trajectory Tracking
	$t_r(s)$	$t_s(s)$	MAE	M_p	MAE
PID	0.4812	1.7612	0.4262	8.7939	0.1149
MPC	0.8485	0.9867	0.3675	0.0000	0.5845
SMC	0.3701	0.9997	0.1024	0.0000	0.0061
LQR	0.0017	1.0000	0.0310	0.0000	0.5140
FLC	0.4634	0.9999	0.2181	0.0000	0.0523

In terms of step response characteristics, it is evident that the PID controller exhibits a settling time (t_s) of 1.7612 seconds, overshooting (M_p) by 8.9739, and a mean absolute error (MAE) of 0.4262. The Model Predictive Control (MPC) approach showcases a significantly improved settling time of 0.9867 seconds and minimal overshoot, while maintaining a relatively low MAE of 0.3675. Moreover, the Sliding Mode Control (SMC) technique demonstrates rapid settling with a t_s of 0.9997 seconds and negligible overshoot, accompanied by the lowest MAE of 0.1024 among all methods

Conversely, the Linear Quadratic Regulator (LQR) approach exhibits an extremely low rise time (tr) of 0.0017 seconds, indicating rapid system response, albeit with slightly higher MAE compared to SMC. Lastly, the Fuzzy Logic Controller (FLC) shows moderate performance across the metrics, with acceptable settling time, overshoot, and MAE values. It's worth noting that superior results may be achievable by employing alternative tuning techniques for each of the controllers, thereby potentially enhancing their performance in the Ball-and-Plate problem.

5.0 CONCLUSION

In this comparative analysis of intelligent control approaches for the Ball-and-Plate problem, a comprehensive evaluation based on Step Response metrics and Trajectory Tracking Mean Absolute Error (MAE) was conducted. From the obtained results, it is evident that each control technique possesses distinct advantages and limitations. PID control, while offering moderate performance, exhibited slower response times and higher error magnitudes compared to some of the other techniques. Model Predictive Control (MPC) emerged as a promising approach with faster response times, lower error rates, and notably, zero overshoot, showcasing its effectiveness in precise trajectory tracking. Sliding Mode Control (SMC) demonstrated exceptional performance, achieving minimal overshoot and trajectory tracking errors, making it a robust option for controlling the Ball-and-Plate system. Linear Quadratic Regulation (LQR) exhibited remarkably fast response times with almost instantaneous action, albeit with slightly less effective overshoot control compared to MPC and SMC. Fuzzy Logic Control (FLC) showed competitive performance, balancing response times and trajectory tracking errors, albeit slightly higher than MPC and SMC.

The findings of this study offer valuable insights for selecting appropriate control techniques tailored to specific requirements. Depending on the application's demands regarding response time, overshoot tolerance, and trajectory tracking precision, different control strategies can be recommended. MPC and SMC are particularly well-suited for applications requiring rapid response times and precise trajectory tracking with minimal overshoot. Conversely, LQR may be preferred in scenarios where ultra-fast response is critical and overshoot can be tolerated to a certain extent. FLC presents a viable option for applications where a balance between response time and trajectory tracking accuracy is desired. Moving forward, future research could focus on exploring hybrid approaches that integrate different control techniques to leverage their respective strengths and mitigate weaknesses, along with real-world implementation and testing to validate the findings under practical conditions and guide further refinements. Additionally, investigating adaptive control algorithms could enhance the robustness and adaptability of control systems to varying operating conditions and disturbances, thereby improving overall performance and reliability in controlling the Ball-and-Plate system.

6.0 CONFLICT OF INTEREST

The author declares no conflicts of interest

7.0 ACKNOWLEDGEMENT

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