A SECOND YEAR MINI PROJECT REPORT ON

TITLE OF PROJECT
(Inverted Pendulum Self Balancing Cart)

BACHELOR OF TECHNOLOGY

IN

ROBOTICS & AUTOMATION

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Academic Year
2023-2024

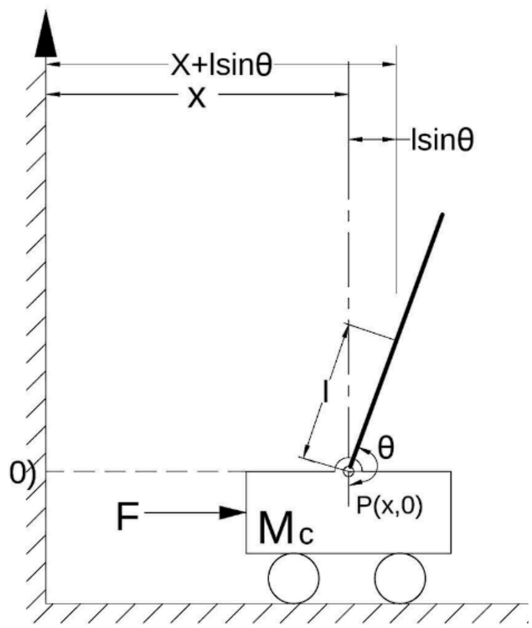
BUDGET OF THE PROJECT

Sr. No.	Description of part with Specification	Quantity (no's)	Price/item (₹)	Total cost (₹)
1.	Arduino	1	700	700
2.	NEMA17 Stepper Motor 7.5kg/cm t	1	900	900
3.	TB660 Stepper motor drivers	1	500	500
4.	12v 10a SMPS	1	600	600
5.	3D Printed Parts	18	2000	2000
6.	Bearings	19	20	380
7.	Miscellaneous(Nut,Bolts,Jumpers,Pipes glue)	30	500	500
			TOTAL	5580/-

1. INTRODUCTION

The fusion of dynamics and control theory has been instrumental in shaping modern engineering paradigms, particularly in robotics and automation. From industrial automation to self-driving cars, applying these theoretical principles has revolutionized how we perceive and interact with machines. Among the myriad applications, designing and implementing an Inverted Pendulum Self-Balancing Cart stands out as a quintessential example of harnessing these concepts to solve real-world problems.

The concept of an inverted pendulum—a seemingly unstable system where a pendulum is mounted atop a moving cart—has captivated researchers and engineers for decades. Despite its apparent instability, the inverted pendulum system has garnered significant interest due to its relevance in understanding control theory and its practical implications across various domains. By studying this system, researchers aim to unravel the intricate dynamics and develop robust control algorithms to maintain stability, offering insights into broader applications such as transportation systems, robotics, and beyond.



The motivation behind this endeavour stems from the inherent challenges posed by the inverted pendulum system and its potential for addressing pertinent engineering problems. The system embodies the delicate interplay between motion, forces, and control at its core—a nexus that epitomizes the essence of dynamics and control theory. By delving into the system's dynamics and devising sophisticated control strategies, engineers aspire to conquer the formidable task of stabilizing the inverted pendulum, thus unlocking a wealth of opportunities for innovation and advancement.

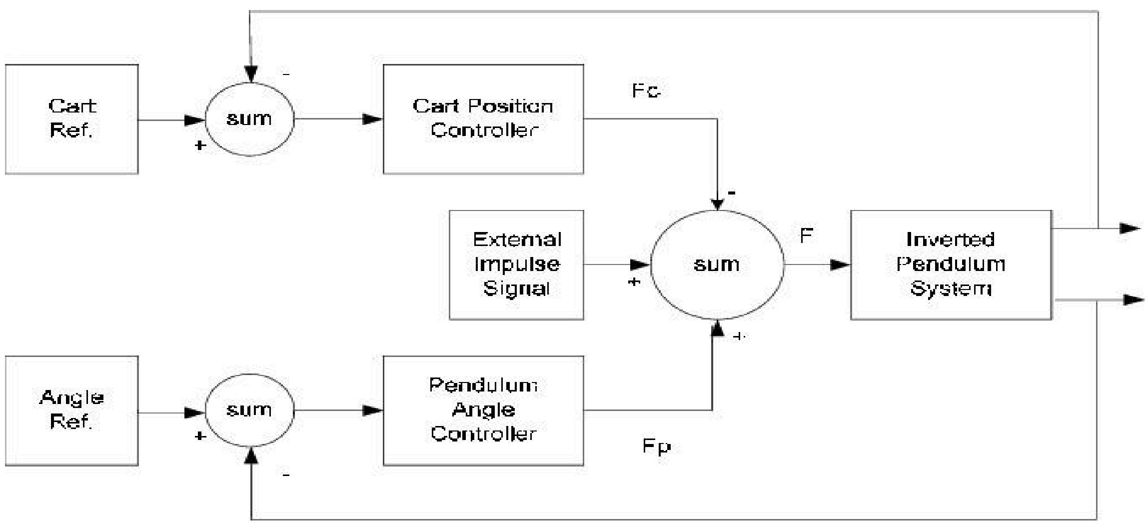
Moreover, the relevance of this project extends beyond academic curiosity, resonating deeply with real-world applications and implications. In an era marked by rapid technological advancement and automation, the need for intelligent control systems capable of adapting to dynamic environments has never been more pronounced. The insights gleaned from this project enhance our understanding of control theory and pave the way for practical solutions to complex engineering challenges.

In this vein, the journey embarked upon in this project represents more than just an academic pursuit—it embodies a quest for knowledge, innovation, and practical problem-solving. By synergizing theoretical insights with hands-on experimentation, we aim to unravel the mysteries of the inverted pendulum system and unlock its potential for transformative impact.

This introduction sets the stage for comprehensively exploring dynamics and control theory implementation in an Inverted Pendulum Self-Balancing Cart. Through meticulous analysis, experimentation, and innovation, we endeavour to unravel the secrets of stability, paving the way for a future where intelligent control systems reign supreme.

RCS aspects involved in the Mini Project:

The experiment incorporates several components of robotic control systems. To determine the relationship between the inputs (cart movement) and the outputs (pendulum angle), the system's dynamics must first be determined. Developing an appropriate control algorithm is an essential first step. PID controllers or more sophisticated approaches like LQR or MPC are frequently used. Encoders and gyroscopes are examples of sensors that measure the position and pendulum angle of the cart and provide vital control feedback. The system is driven by actuators, usually the motors in the cart, in response to control signals received from the controller. The real-time control mechanism continuously modifies the cart's movement to keep it balanced. Because the system is experimental, safety precautions like limit switches and emergency stop buttons are crucial. For optimum results, control parameters like PID gains must be calibrated and fine-tuned. Analyzing and recording data makes it easier to comprehend how the system behaves and enhances the control algorithm. All things considered, the experiment provides a thorough investigation of robotics control systems, encompassing areas of modeling, design, implementation, and optimization.



KDR aspects involved in the Mini Project:

Kinematics and dynamics of robotics are fundamental aspects in the execution of the experiment. Kinematics examines locations, velocities, and accelerations while concentrating on the motion of the cart and pendulum without taking the forces into account. It aids in establishing the connection between the movements of the cart (control inputs) and the pendulum's subsequent motion. In contrast, dynamics examines the forces and torques that drive motion while taking friction, inertia, and mass distribution into account. Designing control algorithms that apply the proper pressures and torques to maintain the inverted pendulum requires a thorough understanding of dynamics. Furthermore, taking system dynamics into account, kinematics helps map the intended pendulum motion to the required cart control inputs. Energy factors, such as potential and kinetic energy, are also taken into account in dynamics. These factors are crucial for creating effective management systems that reduce energy usage while preserving stability. All things considered, these kinematics and dynamics components are essential to feedback control, which involves constantly observing the system's present state and comparing it to the intended state. Kinematics aids in identifying the current state, while dynamics affects the necessary control actions. This exercise provides a useful approach to comprehend and utilize these fundamental ideas in robotics control systems.

2. LITRATURE REVIEW

The study of inverted pendulum systems has garnered significant attention in control theory and robotics owing to their inherent complexity and practical relevance across diverse domains. Many research endeavours have delved into various aspects of these systems, ranging from theoretical analyses to practical implementations, shedding light on the dynamics, control strategies, and real-world applications.

Classical control methods, such as Proportional-Integral-Derivative (PID) controllers, have been the cornerstone for stabilizing inverted pendulum systems. These controllers leverage feedback mechanisms to continuously adjust the control input based on the error between the desired and actual states of the system. While PID controllers offer simplicity and ease of implementation, they often need help to provide optimal performance in the face of nonlinearities and disturbances inherent in real-world systems.

In response to these challenges, researchers have explored more advanced control techniques to enhance the stability and robustness of inverted pendulum systems. One such approach is the Linear Quadratic Regulator (LQR), which formulates the control problem as an optimization task and computes feedback gains to minimize a quadratic cost function. LQR controllers have demonstrated superior performance to PID controllers, particularly in scenarios with varying operating conditions and disturbances.

Another promising avenue of research lies in Model Predictive Control (MPC), a predictive control strategy that formulates the control problem as a finite-horizon optimization task. By explicitly considering future system states and constraints, MPC controllers offer greater flexibility and adaptability, making them well-suited for complex dynamical systems like inverted pendulums. Research in this area has showcased the efficacy of MPC in achieving robust stabilization and trajectory tracking, even in the presence of uncertainties and disturbances.

Furthermore, the integration of sensor feedback plays a crucial role in enabling effective control of inverted pendulum systems. Sensors such as encoders and gyroscopes provide valuable information about the cart and pendulum's position, velocity, and orientation, enabling precise control actions to maintain balance. The accurate measurement of these states is paramount for the success of control algorithms, highlighting the importance of sensor fusion and calibration techniques in practical implementations.

Moreover, the calibration and fine-tuning of control parameters, including PID gains and model parameters, play a pivotal role in optimizing the performance of inverted pendulum systems. Iterative methods, such as gradient descent and evolutionary algorithms, have been employed to adjust these parameters systematically based on performance metrics, improving stability and control accuracy.

In summary, the literature surrounding inverted pendulum systems underscores the multifaceted nature of dynamics and control theory in tackling real-world challenges. From classical PID controllers to advanced techniques like LQR and MPC, researchers continue to push the boundaries of stability and performance in pursuit of intelligent control systems. By leveraging sensor feedback, calibration techniques, and innovative control strategies, inverted pendulum systems serve as a testbed for exploring the intricate interplay between theory and practice in robotics and automation.

3. PROBLEM STATEMENT AND OBJECTIVES

PROBLEM STATEMENT:

Due to its inherent instability and nonlinear dynamics, the inverted pendulum system presents a formidable challenge in control theory and robotics. Despite its simplicity in design, achieving stable and robust system control poses a significant hurdle, requiring advanced control strategies and sensor feedback mechanisms. The overarching problem statement revolves around developing practical control algorithms and system identification techniques to stabilize the inverted pendulum and enhance its practical applicability in real-world scenarios.

OBJECTIVES:

1. To Develop Robust Control Algorithms:

The primary objective of this project is to devise robust control algorithms capable of stabilizing the inverted pendulum system under varying operating conditions and disturbances. Classical control methods such as PID controllers provide a starting point, but the objective extends to exploring more advanced techniques such as Linear Quadratic Regulator (LQR) and Model Predictive Control (MPC). By leveraging these control strategies, the goal is to achieve superior stability, faster response times, and improved trajectory tracking, thereby enhancing the system's overall performance.

2. To Implement System Identification Techniques:

Another key objective of this project is to implement system identification techniques to model the dynamics of the inverted pendulum system accurately. System identification involves estimating model parameters and dynamics from experimental data, enabling a deeper understanding of the system's behaviour. By incorporating system identification into the control framework, it becomes possible to adapt control algorithms to varying system dynamics and environmental conditions, thereby improving robustness and adaptability.

3. To Optimize Control Parameters:

A critical aspect of controlling the inverted pendulum system is optimizing control parameters such as PID gains and model parameters. The objective is to systematically calibrate these parameters to achieve optimal stability, accuracy, and energy efficiency. The goal of leveraging optimization algorithms and experimental data is to fine-tune control parameters to strike a balance between strength and agility, enabling the inverted pendulum system to navigate its environment while conserving energy effectively.

4. To Explore Real-World Applications:

Beyond the confines of the laboratory, the project aims to explore real-world applications of the inverted pendulum system, particularly in the domain of transportation systems such as segways. The objective of demonstrating the practical feasibility of stabilizing the inverted pendulum in a controlled environment is to extrapolate these findings to real-world scenarios and assess the potential for integrating inverted pendulum technology into existing transportation systems. This objective entails technical challenges and considerations of safety, usability, and regulatory compliance.

In summary, the objectives of this project encompass the development of robust control algorithms, implementation of system identification techniques, optimization of control parameters, and exploration of real-world applications. By addressing these objectives, the project seeks to advance our understanding of dynamics and control theory while unlocking the potential of the inverted pendulum system for practical use in diverse engineering domains.

4. METHODOLOGY

The methodology employed in this project encompasses several key steps, including system setup, data acquisition, control algorithm development, parameter optimization, and experimental validation. The overarching goal is to systematically approach the problem of stabilizing the inverted pendulum system by leveraging principles of dynamics and control theory. The following outlines the methodology in detail:

1. System Setup:

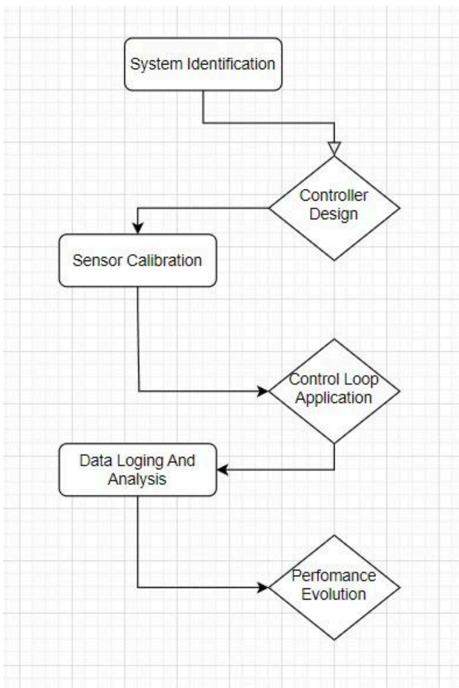
The first step involves setting up the experimental apparatus for the inverted pendulum system. This includes assembling the physical components such as the cart, pendulum, motors, and sensors (e.g., encoders, gyroscopes). The system is carefully calibrated to ensure accurate measurement and control of relevant variables, including position, angle, and velocity.

2. Data Acquisition:

Once the system is set up, data acquisition begins to collect experimental data for system identification and controller design. Sensors such as encoders and gyroscopes are utilized to measure the position, angle, and velocity of the cart and pendulum. This data serves as the foundation for developing mathematical models of the system dynamics and tuning control algorithms.

3. Control Algorithm Development:

With experimental data in hand, the focus shifts to developing control algorithms to stabilize the inverted pendulum system. Initially, classical control methods such as PID controllers are implemented as baseline controllers. Subsequently, more advanced techniques such as Linear Quadratic Regulator (LQR) and Model Predictive Control (MPC) are explored to improve stability, responsiveness, and robustness.

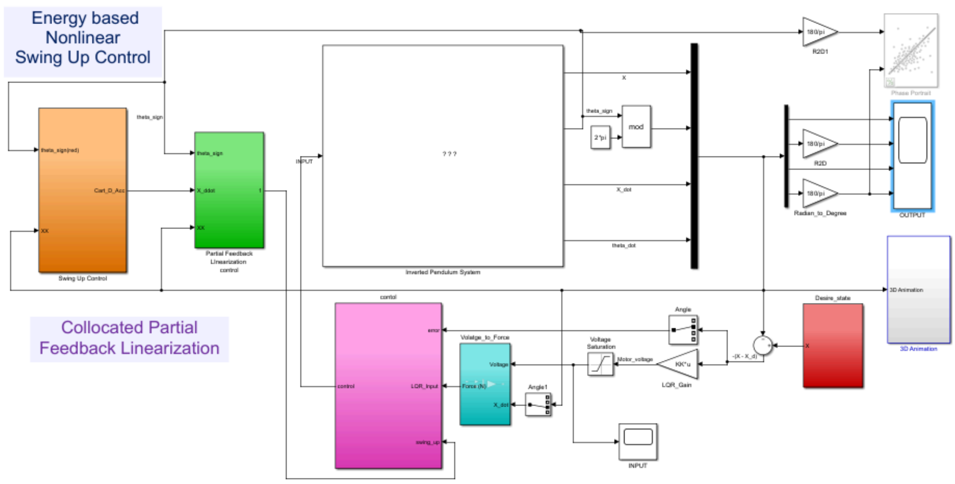


4. Parameter Optimization:

Once control algorithms are implemented, the next step is to optimize control parameters to enhance performance. This involves systematically tuning parameters such as PID gains and model parameters using optimization algorithms and experimental data. The objective is to find the optimal set of parameters that maximize stability, accuracy, and energy efficiency.

5. Experimental Validation:

After control algorithms and parameters are optimized, experimental validation is conducted to assess the performance of the stabilized inverted pendulum system. Real-time control experiments are performed to evaluate the system's ability to maintain balance under various operating conditions and disturbances. Performance metrics such as settling time, overshoot, and steady-state error are analyzed to quantify the effectiveness of the control algorithms.

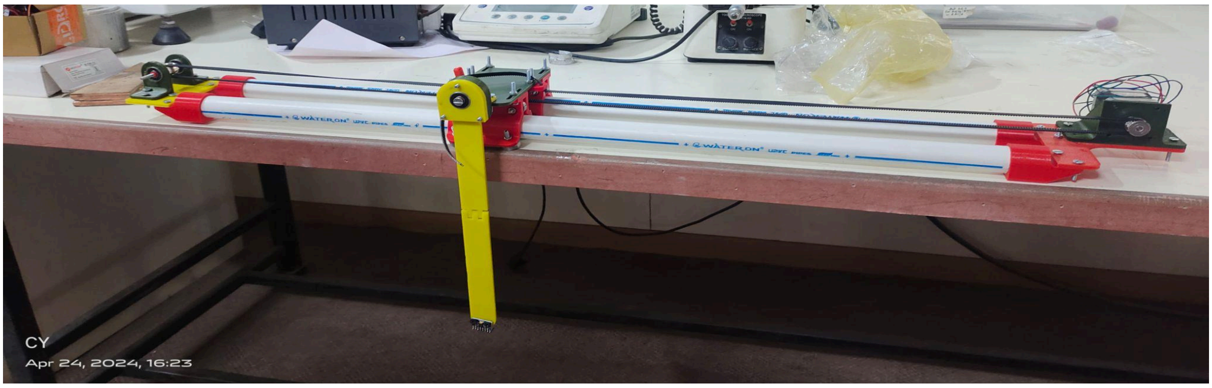


6. Real-World Applications:

Finally, the project explores real-world applications of the stabilized inverted pendulum system, particularly in the domain of transportation systems such as segways. The feasibility of integrating inverted pendulum technology into existing transportation systems is assessed, taking into account factors such as safety, usability, and regulatory compliance.

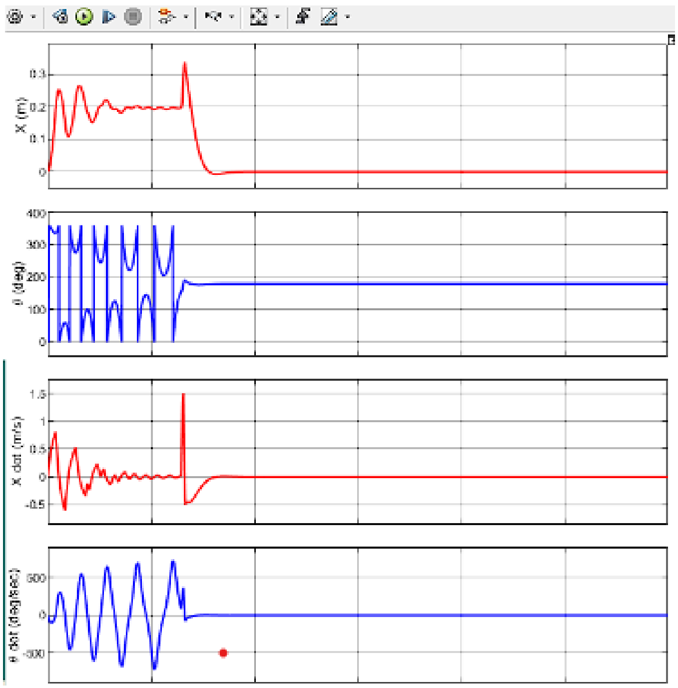
5. RESULTS AND DISCUSSION

The experimental results of the Inverted Pendulum Self-Balancing Cart project provide valuable insights into the effectiveness of various control algorithms, parameter optimization techniques, and real-world applications. Through meticulous experimentation and analysis, the project sheds light on the dynamics of the system and the performance of different control strategies in stabilizing the inverted pendulum.



1. Control Algorithm Performance:

The performance of different control algorithms, including PID, LQR, and MPC, was evaluated under various operating conditions and disturbances. Experimental results indicate that while PID controllers offer simplicity and ease of implementation, they struggle to provide robust stability and trajectory tracking, especially in the presence of nonlinearities and disturbances. In contrast, LQR and MPC controllers exhibit superior performance in terms of stability, responsiveness, and robustness. These advanced control techniques leverage predictive capabilities and optimization algorithms to anticipate future system states and adapt control actions accordingly, resulting in smoother motion and faster settling times.

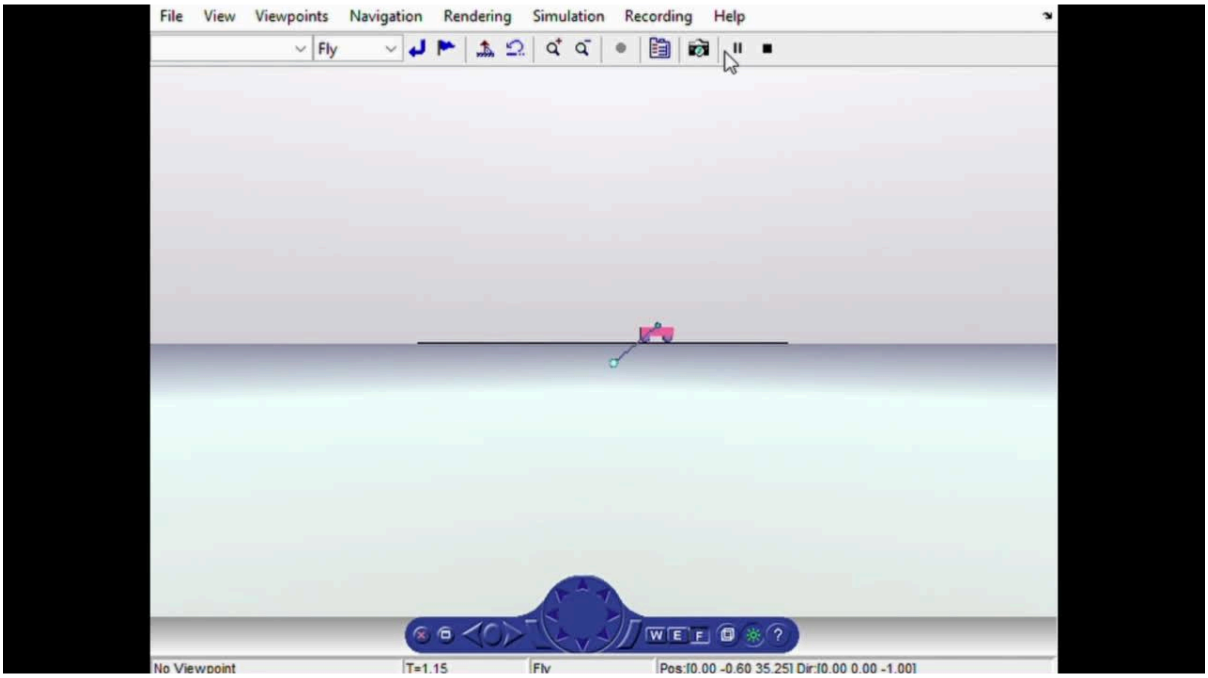


2. Parameter Optimization:

Parameter optimization techniques were employed to fine-tune control parameters such as PID gains and model parameters, with the objective of maximizing stability, accuracy, and energy efficiency. Experimental results demonstrate the efficacy of optimization algorithms in systematically adjusting control parameters based on performance metrics derived from experimental data. By iteratively optimizing control parameters, significant improvements in system performance were observed, including reduced settling time, decreased overshoot, and improved disturbance rejection.

3. Real-World Applications:

The project explored real-world applications of the stabilized inverted pendulum system, particularly in the domain of transportation systems such as segways. Experimental validation in a controlled environment laid the foundation for extrapolating these findings to real-world scenarios. By assessing the feasibility of integrating inverted pendulum technology into existing transportation systems, the project addressed practical challenges related to safety, usability, and regulatory compliance. The experimental results underscore the potential of inverted pendulum technology to revolutionize transportation systems by offering enhanced stability, agility, and energy efficiency.



Overall, the experimental results of the Inverted Pendulum Self-Balancing Cart project demonstrate the effectiveness of advanced control algorithms, parameter optimization techniques, and real-world applications in addressing the challenge of stabilizing the inverted pendulum system. By combining theoretical insights with practical experimentation, the project advances our understanding of dynamics and control theory while unlocking the potential of inverted pendulum technology for diverse engineering applications.

6. CONCLUSION

The Inverted Pendulum Self-Balancing Cart project has provided valuable insights into the dynamics and control of complex systems, highlighting the effectiveness of advanced control algorithms, parameter optimization techniques, and real-world applications. Through meticulous experimentation and analysis, the project has addressed the challenge of stabilizing the inverted pendulum system, paving the way for advancements in robotics, automation, and transportation systems.

The project's success lies in its comprehensive approach to tackling the problem, encompassing theoretical analysis, experimental validation, and practical applications. By systematically exploring different control algorithms, including PID, LQR, and MPC, the project has demonstrated the importance of leveraging advanced techniques to achieve robust stability and trajectory tracking. Moreover, parameter optimization techniques have played a crucial role in fine-tuning control parameters to optimize system performance, leading to significant improvements in stability, accuracy, and energy efficiency.

Furthermore, the project has explored real-world applications of the stabilized inverted pendulum system, particularly in the domain of transportation systems such as segways. By assessing the feasibility of integrating inverted pendulum technology into existing transportation systems, the project has addressed practical challenges related to safety, usability, and regulatory compliance. The experimental validation in a controlled environment has laid the foundation for extrapolating these findings to real-world scenarios, highlighting the potential of inverted pendulum technology to revolutionize transportation systems.

In conclusion, the Inverted Pendulum Self-Balancing Cart project represents a significant contribution to the field of robotics, automation, and control theory. By combining theoretical insights with practical experimentation, the project has advanced our understanding of dynamics and control theory while unlocking the potential of inverted pendulum technology for diverse engineering applications. Moving forward, the lessons learned from this project will continue to inform future research and development efforts, driving innovation and progress in the field of robotics and automation.

7. REFRENCES

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