“Development and Construction of an Inverted Pendulum Balancing Device”

Bobadilla Dranrev, Del Mundo Aldous John, Didulo Ric Joseph, Peliña Lance Zedech, Puso Rocxel Roi
College of Engineering
School of Technology
First Asia Institute of Technology and Humanities

I. INTRODUCTION

Background of the Project

The development and construction of an inverted pendulum balancing device represent a significant area of study within the fields of control systems, robotics, and mechatronics. This endeavor involves creating a mechanical system that can balance an inverted pendulum in an upright position, despite the inherent instability of such a configuration.

An inverted pendulum consists of a pendulum rod with a mass attached to one end, suspended vertically from a pivot point. The challenge lies in maintaining the pendulum in an upright position, as any slight deviation from the vertical will cause it to fall. Achieving this balance requires precise control of the system's dynamics, typically through the application of feedback control techniques.

This study is motivated by both theoretical and practical considerations. From a theoretical standpoint, inverted pendulum systems serve as ideal testbeds for exploring and validating control algorithms. Their nonlinear and unstable nature poses a challenging control problem, making them excellent subjects for research in control theory.

Practically, inverted pendulum balancing devices have a wide range of applications across various industries. For instance, similar principles are employed in the stabilization of unmanned aerial vehicles (drones), self-balancing robots, and even in the design of control systems for personal transportation devices like segways. By studying and developing inverted pendulum systems, researchers and engineers gain insights into complex control problems and contribute to advancements in technology.

The construction of an inverted pendulum balancing device involves several key steps. First, a suitable mechanical design must be developed to ensure stability and maneuverability of the system. This design may incorporate components such as a cart or platform for supporting the pendulum, along with actuators for controlling its position.

Next, sensors are employed to measure the orientation of the pendulum and provide feedback to the control system.

Common sensors used in this context include accelerometers, gyroscopes, and encoders. These sensors enable the control system to continuously monitor the position of the pendulum and make adjustments as necessary to maintain balance.

The control algorithm implemented in the system plays a crucial role in achieving stable balance.Using Arduino mega 560 control is a commonly used technique for controlling inverted pendulum systems. This algorithm adjusts the control inputs based on the difference between the desired setpoint (vertical position) and the measured orientation of the pendulum.

Through iterative testing and refinement, researchers fine-tune the control parameters to optimize the performance of the system. This process involves evaluating the system's stability, responsiveness, and robustness to disturbances. By experimenting with different control strategies and hardware configurations, researchers gain valuable insights into the dynamics of inverted pendulum systems and advance the state-of-the-art in control theory and robotics.

In addition to research and development efforts, inverted pendulum balancing devices have educational value. They serve as practical demonstrations of control theory concepts and provide hands-on learning opportunities for students. Building and experimenting with these systems help students develop a deeper understanding of feedback control, system dynamics, and real-world applications of engineering principles.

II. Objective of the Project

1. The main objective of this project is to Explore the integration of inverted pendulum principles into robotics and automation..
2. To Analyze the behavior of the system in its whole..
3. To Develop and Optimize control algorithms taking robustness..

4. Examine how inverted pendulum concepts may be used in robotics and automation.
5. Apply Transfer Function to the design created

Statement of the problem

The inverted pendulum system shows that the domain of control systems is frequently employed to explain fundamental concepts in linear control theory, particularly concerning the stabilization of systems prone to instability. Beyond its utility in linear control, this system also offers valuable insights into the principles of nonlinear control theory. At its essence, the system exhibits inherent nonlinear dynamics, rendering it a compelling subject for exploring various nonlinear control strategies.

Within this configuration, an inverted pendulum is affixed to a motor, giving rise to a dynamic interplay between the pendulum's precarious equilibrium and the motor's capacity to influence its motion. This setup encapsulates the essence of control theory, as it necessitates strategic interventions to uphold stability and prevent the pendulum from falling. A slight perturbation could easily lead to the overturning of an inverted pendulum, rendering it as unstable as attempting to balance a stick on its end. Unlike a conventional pendulum that naturally oscillates back and forth, an inverted pendulum demands constant adjustments to sustain its upright position. Without meticulous control, it swiftly deviates from equilibrium. Due to this inherent instability, managing an inverted pendulum presents a formidable challenge, necessitating the application of sophisticated engineering and advanced control theory techniques to achieve stabilization.

Scope and Limitation of the Project

This Project aims to build and code using Arduino as microcontroller to an inverted pendulum. Arduino Microcontroller is a very effective type of microcontroller used in inverted pendulum, it makes the inverted pendulum work better and easier to code in some instances. The flexibility of Arduino allows for real-time feedback control, enabling stabilization to adjust inverted Pendulum in upright position. In addition, Arduino is much more compatible in communication than other microcontrollers that are more complex and harder to understand.

This project focuses more on Inverted pendulum using Arduino and its memory constraints are limited only. The complex algorithms may be affected because it requires high computational resources, and this will be a big problem that could affect our Inverted Pendulum to execute real- time. Inverted Pendulum has limited application in Real-world, and Inverted Pendulum has high complexity that might affect the building progress.

Review of related literature

The task of balancing an inverted pendulum without explicit feedback presents a significant challenge in control systems and reinforcement learning. Traditional control methods, like PID controllers, require precise knowledge of system dynamics and continuous feedback, limiting their applicability when such information is unavailable. In response, reinforcement learning (RL) has emerged as a promising approach, allowing agents to learn optimal control policies through interaction with the environment. Early RL approaches relied on continuous performance feedback, but in scenarios where feedback is only given upon failure, RL agents must learn under uncertainty and delayed reinforcement. Bayesian RL methods have been proposed to model uncertainty, while temporal-difference (TD) learning algorithms, such as Q-learning and SARSA, have been adapted to address the challenges of learning with delayed feedback. These methods update value estimates based on temporal differences between predicted and observed rewards, enabling agents to learn efficiently despite delayed reinforcement. Given the nonlinear dynamics of the inverted pendulum, function approximation techniques, including neural networks, have been employed to represent and approximate the required control policies. However, ensuring stability and convergence of RL algorithms remains a key challenge. Future research may explore hybrid control methods combining RL with model-based approaches and investigate the transferability of learned policies to real-world robotic systems.

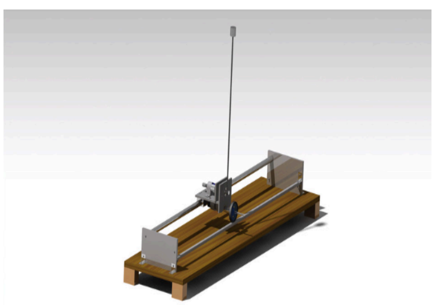
The inverted pendulum problem has long been a classic benchmark in control theory and dynamics, captivating researchers and enthusiasts alike with its inherent instability and complex control requirements. The Instructables article titled "Inverted Pendulum: Control Theory and Dynamics" by **KousheekC (2019)** provides a comprehensive exploration of the theoretical concepts and practical implementations associated with controlling an inverted pendulum system.

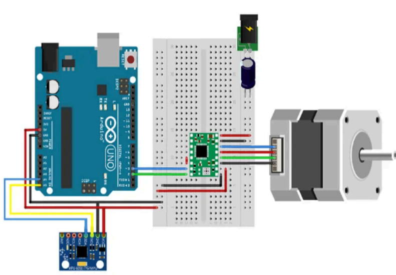
In their study, Loram et al. challenge the traditional understanding of continuous feedback mechanisms in physiological control systems, particularly in the context of maintaining body position. They introduce the concept of intermittent control using gentle taps to stabilize an unstable load, akin to a person fainting. This approach proves to be more natural, effective, and robust to unexpected changes compared to continuous hand contact. Through experimentation with a joystick-controlled system, they demonstrate that intermittent control, optimized at a frequency of two taps per second, can explain the upper frequency limit of control by both intermittent and continuous methods. The authors propose serial ballistic control as a new physiological paradigm for interpreting sustained control of posture and movement, highlighting its relevance in understanding homeostasis and motor control mechanisms.

Pasma et al. investigate the parameters of the Independent Channel (IC) model, a commonly used balance control model, to discern their unique contributions and relative importance in describing balance behavior. They express balance behavior through transfer functions (TFs), representing the relationship between sensory perturbations and body sway in terms of amplitude and phase. Using partial derivatives, they determine the local sensitivity of each parameter for both magnitude and phase. Their findings reveal that parameters such as intrinsic stiffness and proportional gain significantly shape magnitude at low frequencies, while derivative gain influences peak and slope magnitude between specific frequency ranges. Sensory weight impacts overall magnitude without affecting phase, while time delay becomes apparent in phase modulation at higher frequencies. Parameters related to force feedback have less influence compared to others. The study emphasizes the importance of understanding parameter contributions in delineating balance behavior, particularly in distinguishing between different patient groups.

III. Methodology

Design and Simulation





The wiring consists of connecting the MPU6050 to the Arduino and the wiring of the drive system. Follow the wiring diagram attached above to connect each component.

Stepper motor to stepper driver:

- Coil 1(a) to 1A
- Coil 1(b) to 1B
- Coil 2(a) to 2A
- Coil 2(b) to 2B

Stepper Driver to Arduino:

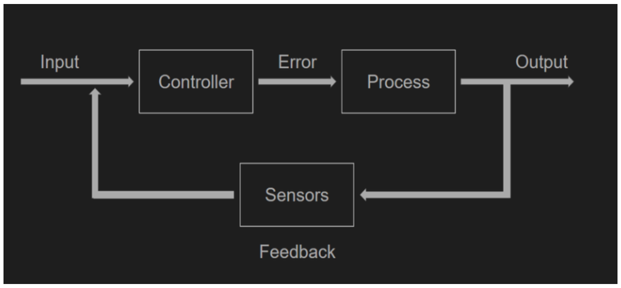
- GND to GND
- VDD to +5v
- STEP to D3
- DIR to D2
- VMOT to power supply's positive terminal
- GND to power supply's ground terminal

The Sleep and Reset pins on the stepper driver need to be connected with a jumper. And finally, it is a good idea to connect an electrolytic capacitor of about 100 uF in parallel with the positive and ground terminals of the power supply.

Designing an inverted pendulum balancing machine involves meticulous planning and integration of various components. The mechanical structure forms the foundation, providing stability and support for the pendulum and its associated elements. Sensors, such as accelerometers and gyroscopes, play a pivotal role by continuously measuring the pendulum's position and angle, feeding crucial data to the control system. This system, often based on PID control algorithms, analyzes the sensor inputs and orchestrates the corrective actions required to maintain the pendulum's balance. Actuators, ranging from motors to hydraulic systems, enact these adjustments based on the control system's commands, creating a seamless feedback loop. Calibration and fine-tuning are essential to optimize performance and ensure precise control over the balancing process. Safety measures, including emergency stops and physical barriers, are implemented to safeguard operators and prevent accidents, especially in high-speed or heavy-duty applications.

In operation, the inverted pendulum balancing machine showcases the principles of closed-loop feedback control systems in action. As sensors detect deviations from the desired position, the control system swiftly calculates the necessary corrective actions, which are then executed by the actuators. This continuous cycle of measurement, analysis, and adjustment enables the machine to effectively counteract external disturbances and maintain the pendulum's equilibrium. Through calibration and tuning, the system's performance can be optimized for stability and responsiveness, ensuring reliable operation across various conditions. Safety features are paramount to protect operators and equipment, mitigating risks associated with potential malfunctions or accidents. Overall, the inverted pendulum balancing machine serves as a practical demonstration of control theory concepts while offering a versatile platform for experimentation and learning.

Block Diagram



Control theory is a subfield of mathematics that deals with controlling and operating dynamical systems in engineered processes and machines. The objective is to develop a control model or a control loop to generally achieve stability. In our case, balance the upside down pendulum.

There are two main types of control loops: open loop control and closed loop control. When implementing an open loop control, the control action or the command from the controller is independent of the system's output. A good example of this is a furnace, where the amount of time that the furnace remains on is purely dependent on the timer.

Whereas in a closed loop system, the controller's command is dependent on the feedback from the state of the system. In our case, the feedback is the angle of the pendulum with reference to the normal which determines the speed and position of the cart, therefore making this system a closed loop system. Attached above is a visual representation in the form of a block diagram of a closed loop system. There are several feedback mechanism techniques but one of the most widely used is the proportional–integral–derivative controller (PID controller), which is what we are going to use.

IV. **RESULTS AND ANALYSIS**

PARAMETERS	QUANTITY	PRICE
Servo motor	1	86 PHP
Stainless Rod	1	
Accelerometer	1	84 PHP
DC Motor	1	150 PHP
CVT belt	1	

V. **CONCLUSION AND RECOMMENDATION**

The Inverted Pendulum Balancing Machine represents a remarkable fusion of advanced control algorithms and mechanical engineering. Its ability to maintain stability in dynamically unstable systems opens doors to numerous applications, from robotics to aerospace. However, further research is necessary to optimize its efficiency and robustness in real-world scenarios, ensuring its viability across various industries.

The Inverted Pendulum Balancing Machine showcases the power of feedback control systems in overcoming inherent instability. Its potential to enhance automation and control processes is evident, promising advancements in manufacturing, transportation, and beyond. Nonetheless, addressing challenges such as noise sensitivity and response time will be crucial for its widespread adoption and practical implementation.

The Inverted Pendulum Balancing Machine epitomizes the marriage between theoretical control principles and practical engineering solutions. Its ability to stabilize inherently unstable systems highlights a paradigm shift in control theory. As research continues to refine its capabilities and address scalability issues, this technology holds immense promise for revolutionizing industries reliant on precise and stable control systems.

The Inverted Pendulum Balancing Machine underscores the importance of interdisciplinary collaboration in pushing the boundaries of control theory and mechanical design. Its success in maintaining equilibrium in challenging environments demonstrates the synergy between innovation and application. However, future endeavors should focus on streamlining its design for commercial viability and exploring potential adaptations for diverse industries, paving the way for widespread adoption and technological advancement.

The Inverted Pendulum Balancing Machine stands as a testament to human ingenuity in conquering complex control problems. Its capacity to stabilize unstable systems has profound implications for automation, transportation, and beyond. Moving forward, continued research and development efforts will be essential in refining its performance, ensuring its seamless integration into real-world scenarios and catalyzing transformative changes across various sectors.

VI. REFERENCES

[1] Boubaker O. (2013). The Inverted Pendulum Benchmark in Nonlinear Control Theory: A Survey.

[2] IEEE. (2012). The inverted pendulum: A fundamental benchmark in control theory and robotics.

[3] Wang J.(2009). Simulation studies of inverted pendulum based on PID controllers.

[4] Milton et al.(2009). The time-delayed inverted pendulum: Implications for human balance control.

[5] *Control Tutorials for MATLAB and Simulink - Inverted Pendulum: System Modeling*. (2024). Umich.edu. https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling&fbclid=IwAR3iQhkq9OEcpfbhrMlSD9Y3Fb8F58dSNRZJv_Wf_txIdqdTDryGD9EHNek_aem_ARuHYBItliBRa98iu415dcJOF6wXeULdq0ZUcRm9JQtDkKRzaurQ7wIGz0kJe00F6j8ltrP4srj1Vo-pFUsf2Fcp

[6] KousheekCMore. (n.d.). *Inverted Pendulum: Control Theory and Dynamics*. Instructables. https://www.instructables.com/Inverted-Pendulum-Control-Theory-and-Dynamics/

[7] C.W. Anderson. (n.d.). Learning to control an inverted pendulum using neural networks.

[8] Loram, I. D., Gollee, H., Lakie, M., & Gawthrop, P. J. (2011). Human control of an inverted pendulum: Is continuous control necessary? Is intermittent control effective? Is intermittent control physiological?.