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RESEARCH ARTICLE

# Design and Implementation of Remote Lab PID Controller Experiment Based on IoT

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**ABSTRACT**
The education sector has increasingly embraced distance education to ensure a safe and uninterrupted learning process, especially in wars or epidemics. This paper focuses on designing and implementing a PID (Proportional-Integral-Derivative) controller experiment in remote laboratories utilizing the Internet of Things (IoT). Also, a laboratory experiment was developed using a naturally unstable system, specifically a cart-inverted pendulum. The experiments aim to enhance students' understanding of PID controller tuning within a real-world context. This system was chosen due to its dual motion characteristics, with a linear motion for the cart and a circular motion for the pendulum. Two controllers were designed and implemented for the system to enable control and feedback. Additionally, the Blynk platform was integrated into the experiment setup, allowing for real-time visualization of the system's response, control of PID parameters, and the ability to view the video stream via platforms like Skype. For remote connectivity, NodeMCU, an IoT development board, controlled the pendulum, collected system parameters, and transmitted them to the cloud through the Internet. Moreover, the sensors and the system were mathematically modeled, and their transfer functions were extracted. That allows the students to do the PID experiment theoretically and practically and compare the results. This complete setup enables local and remote access to the experiment, ensuring students can experiment regardless of their physical location. As a result of the study, designing and implementing a remote laboratory PID controller experiment utilizing IoT technology provides students with an innovative and immersive learning experience.

**Keywords:** Smart laboratory system, Internet of Things (IoT), Proportional-Integral-Derivative (PID), Remote laboratory, Blynk, Inverted Pendulum, NodeMCU

## 1. Introduction

Online education has surged in importance recently due to various factors such as health concerns [1], security issues like the COVID-19 pandemic [2], and conflicts [3], which have disrupted numerous societal domains, including education. In response, some governments have imposed curfews to prevent the spread of the virus and mitigate infection rates [4]. Also, many educational institutions, particularly universities, have shifted their focus towards online learning, specifically leveraging the Internet of Things (IoT). Utilizing virtual and innovative laboratories aims to address the limitations associated with the practical aspects of education, thereby bridging the gap between theory and practice [5]. This approach ensures that students gain valuable practical experience, enhancing their scientific competence, which is pivotal for their successful transition into the workforce upon graduation [5]. The prominence of online education continues to grow, especially considering the evolving landscape influenced by factors like health and security [6], which disrupt various facets of society, including the education sector [7].

Universities increasingly turn to online education utilizing IoT technology [8], [9] to bolster their offerings, particularly in online and intelligent laboratories. This strategic shift aims to bridge the gap between theoretical and practical education, ensuring students maintain crucial hands-on experience essential for their future careers without compromising their academic rigor. Conventional classroom settings often struggle with large student-to-teacher ratios, particularly prevalent in developing nations, necessitating more classrooms with fewer students. This scenario significantly burdens educators, requiring them to manage large cohorts within limited timeframes, often proving arduous and ineffective [10]. In contrast, virtual and remote laboratories mitigate the logistical challenges of traditional setups and offer cost-effective solutions, particularly in scenarios where dangerous experiments, epidemics, or conflicts disrupt access to physical facilities.

Advancements in information technologies have catalyzed a revolution in educational methodologies, ushering in unprecedented opportunities for innovation. Pioneering studies, such as those conducted by Fabregas et al., showcase the transformative potential of remote laboratories (RLs) in engineering education. Interactive RLs have been developed through platforms like Simulink and Easy Java Simulations (EJS), offering immersive learning experiences [11]. Responding to the evolving demands of the fourth industrial revolution, initiatives like ELLI, spearheaded by the German Federal Ministry of Education and Research (BMBF), are driving advancements in engineering education. TU Dortmund University, for instance, is at the forefront of this movement, pioneering remote and virtual labs tailored to mechanical engineering disciplines. Innovations such as tele-operative material characterization testing cells and remote labs for incremental tube forming underscore a commitment to practical, industry-aligned education [12]. Technologies like Augmented Reality and Additive Manufacturing further exemplify this dedication to preparing students for real-world challenges and opportunities.

### 1.1. Contributions

The contributions of this paper are as follows:

- Contribute to advancing distance education, promote practical learning experiences, and enable students worldwide to access and benefit from laboratory experiments through remote access and IoT technology.
- Enhance knowledge of PID controller tuning by providing a practical application that bridges the gap between theoretical concepts taught in the classroom and real-world experiments.
- Allow students to gain a deeper understanding of the subject matter and prepare them for the labor market, fostering innovation and creativity. The system allows for modifying PID controller values.
- Address the need for distance education in the education sector, particularly in areas where traditional -educational processes are hindered by factors such as wars, lack of resources, or epidemics like the COVID-19 pandemic.

The rest of this paper is organized as follows: Sect. 2 presents the literature review on automation and remote control based on IoT. The proposed system is introduced in Sect. 3 with the real-case scenario. Sect. 4 details the study and points to some possible future works. Sect. 5 concludes the research and points to some possible future works.

## 2. Literature Review

The conceptualization and execution of remote laboratory PID controller experiments are central themes in the literature, alongside pertinent research in this domain. Integrating practical experiments is paramount in enhancing the educational paradigm by bridging the gap between theoretical knowledge and real-world applications, thereby fostering a more profound understanding among students. Among the notable studies in this area, Issa et al. engineered a teleoperated 3D printer featuring a robotic arm capable of executing and regulating the printing process from any location globally, leveraging connectivity with the Repetier-Host platform [13]. However, a notable limitation arises in applying Labview HTML within the video stream of the pendulum, manifesting as a delay of several seconds between the actual pendulum response and its depiction on the Labview HTML interface. This delay adversely impacts the experiment's efficacy, particularly considering the high sensitivity of the controller to temporal factors, potentially leading to student confusion. Colak et al. introduced an innovative web-based DC motor laboratory termed NeTRe-LAB aimed at augmenting the teaching of electrical machines. Nevertheless, this laboratory presents certain drawbacks, notably the requirement for a more substantial investment in equipment, including a DAQ board, Hub, and assorted services, as shown in Figure 1.

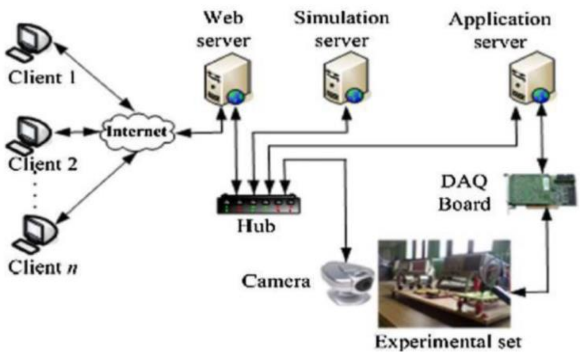


Figure 1. Hardware Structure of the NeTRe-LAB [14]

The NeTRe-LAB encounters sluggish response times contingent upon network velocity and system demands. In contrast, the proposed system exhibits superiority over NeTRe-LAB in both aspects by employing cost-effective equipment for experiment setup and demonstrating rapid response times [14]. Kaçar et al. introduced AnalogWeb, a web-based MATLAB simulation for analog modulation techniques, as an integral component of Analog Communication [15]. Ramya et al. devised a laboratory setup for conducting experiments on actuators and sensors, aiming to enhance their application in engineering education and industrial contexts [16]. In chemical engineering, a remote distillation column experiment was pioneered at the Institute of Process and Plant Technology [17]. Güney et al. explored the utilization of thermal sensors on mobile platforms for detecting living entities, focusing on monitoring body temperatures and the spatial distribution of COVID-19 outbreaks [18]. Benitez et al. innovated a robotic arm system for online robotics instruction during pandemic contingencies, comprising the robotic arm itself, an Internet control unit, and a user interface [13]. Additionally, the Internet of Things (IoT) extends its reach beyond educational and laboratory settings, permeating into diverse domains such as smart homes, urban environments, and industrial operations as shown in Figure 2.

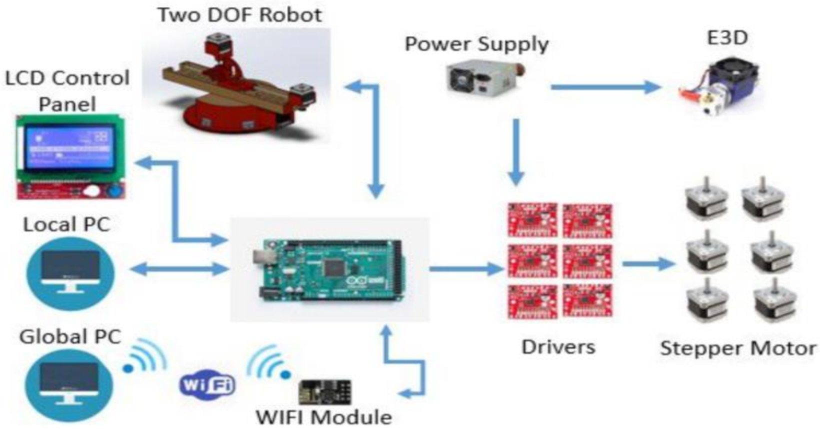


Figure 2. Schematic of the Developed Teleoperated 3D Printer System [19]

Küçük et al. introduce an Internet of Things (IoT) system tailored to motivate students in studying the development and implementation of IoT applications in real-time [20]. Additionally, various studies are available for broader application, facilitating performance comparisons within specific test scenarios [21]. Senese et al. have developed a web interface enabling students to remotely conduct experiments on rapid chemical reactions in real-life settings rather than simulations. This hands-on experience provides interactive technical support and fundamental knowledge exchange, enhancing student engagement. The system facilitates data sharing and analysis, effectively utilizing costly equipment and broadening student access across various universities [22]. Naef conducted an analytical chemical experiment utilizing headspace gas chromatography (GC). Three methods were employed, with a focus on the internet-based approach. While essential tools were utilized in the experiments, only the internet-based method was discussed, as shown in Figure 3 [23].

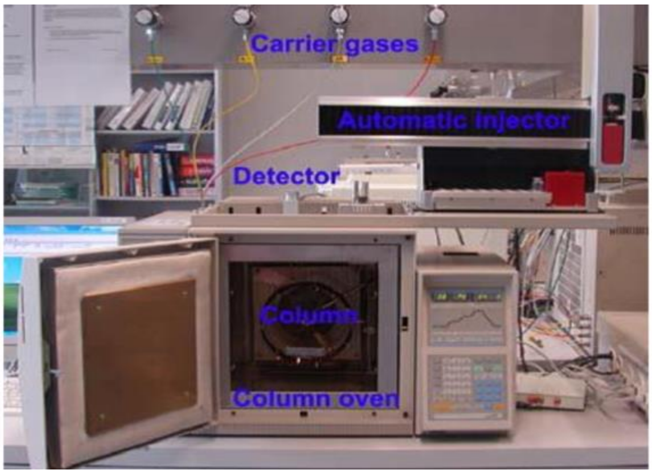


Figure 3. The Chromatography Lab Setup

Technology has emerged as a critical tool for maintaining student engagement in response to the COVID-19 pandemic's disruption of traditional education. The development of an Augmented Remote Lab (ARL) by Nicolette et al. sought to address this challenge by providing a platform for remote learning. Results from the investigation demonstrated notable increases in student motivation, particularly in attention, relevance, and satisfaction, highlighting the potential of remote labs to effectively engage students and facilitate learning experiences in unprecedented circumstances [24]. This study addresses the importance of practical work (PW) in exact sciences and introduces an IoT-based approach for remote experimentation in analog electronics. AM Taj et al. propose a low-cost system utilizing the Red Pitaya STEMLab board for remote manipulation, enabling intelligent selection of integrated practical works. Their analysis emphasizes minimizing latency and enhancing portability to streamline learning experiences while maintaining quality, demonstrated through a comparison with traditional hands-on laboratory methods as shown in Figure 4 [25].

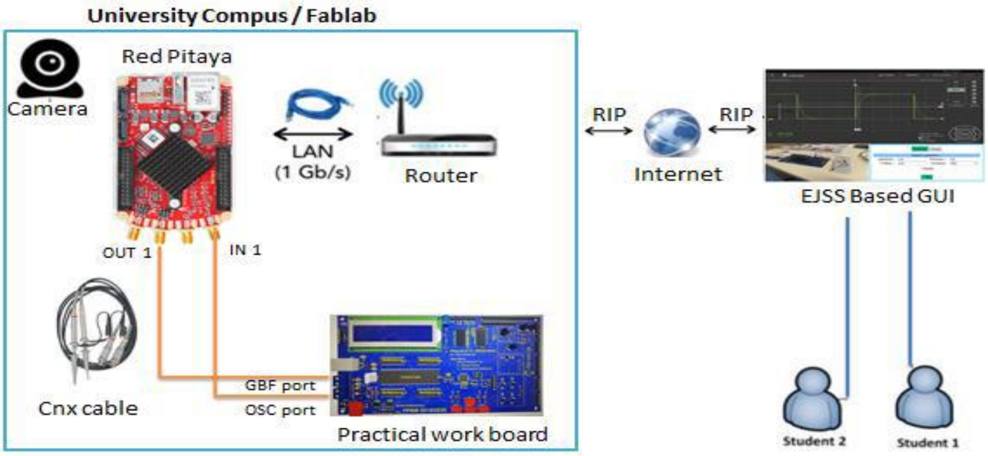

Figure 4. A General Architecture for the Remote IoT System for Practical Work

## 3. Design and Implementation of the Proposed System

This section presents the design stages and system components in detail. To set up a successful establishment of the educational laboratory and achieve the expected results, it must consist of several elements and components that have compatibility and synchronization, so the system consists of three structures as follows.

### 3.1. Mechanical System Structure

An inverted pendulum, shown in Figure 5, is a classical dynamic system that is unstable because it falls on its own, given that its stability is upwards, and this can only be achieved by using control systems. In this paper, the PID controller was used to balance the pendulum. The mechanical part of an inverted pendulum system consists of a cart, in the middle of which an inverted pendulum is installed with a rotary bearing that allows it to rotate freely with very little friction. The inverted pendulum is a one DOF system considered a good and low-cost tool for testing control strategies. Moreover, it is easy because it can be viewed as a linear system. The process of balancing the pendulum is done by moving the cart using a motor that is tied to the cart with a belt according to the values of the angle of the pendulum with the cart. The PID controller makes the necessary calculations and sends the appropriate signal to the motor to move the cart and ensure the balance of the pendulum [26], [27].

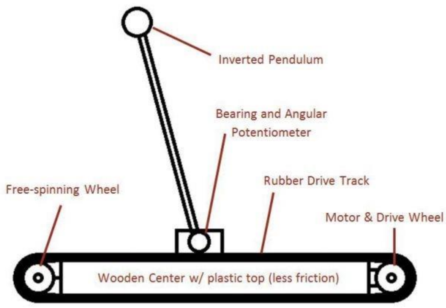

Figure 5. Schematic of Inverted Pendulum Hardware Setup

### 3.2. Electronic System Hardware

The electronic structure includes a NodeMCU board to perform the PID algorithm and connect the experiment with the internet to send the values of the encoders that have been read and send commands to the DC motor driver to control the motor, as shown in Figure 6. Just before the current was delivered to the motor, the current amplification was done using an H-Bridge DC motor (L298N). Absolute rotary encoders provided the cart with linear movement and angled the pendulum with the cart. A mobile device is used as an IP camera to provide a real-time video stream of the experiment via the Skype application. The developed GUI was designed using the Blynk platform to control the experiment hardware using controls to tune the PID parameters and display the system response in real time.

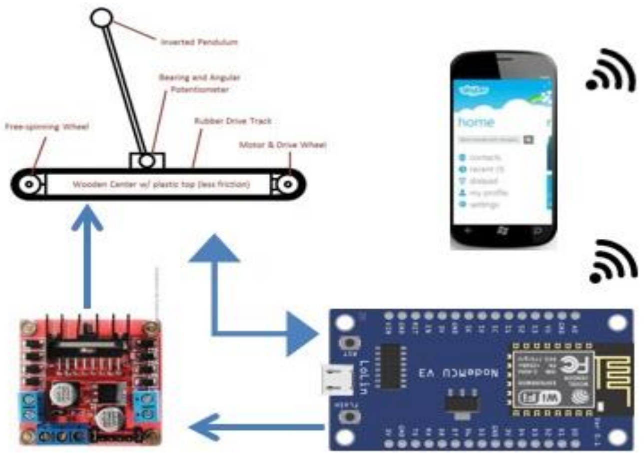


Figure 6. Electronic Control of System Hardware

### 3.3. System Software Design

The student can observe the real-time video effect of tuning the PID parameters on the Skype platform, as shown in Figure 7. This effect is achieved by setting video calls to auto-response, enabling students to view the experiment immediately upon making a video call on the local mobile device used as an IP camera. The developed Blynk GUI, comprises several sliders, chart displays, and buttons. Through these icons and widgets, students can adjust PID parameters using the sliders, send these values to the cloud using the buttons, and visualize the reaction or response of the pendulum on the chart, as shown in Figure 8. Additionally, the Skype platform was utilized for real-time observation of the experiment. Furthermore, the Blynk app allows students to visualize the pendulum's response as a waveform and modify the PID parameters.

Figure 7. Showing Live Video Stream of Inverted Pendulum Via Skype

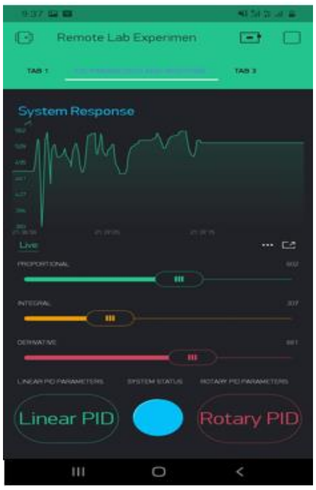


Figure 8. GUI Showing the Time-Response of Inverted Pendulum and PID Controller Values on the Blynk Platform

## 4. System Modeling

System modeling involves converting the physical system into a set of mathematical equations. This step is crucial in system development as it allows for analyzing the system's performance and behavior before implementation. Mathematical modeling can save time and resources, particularly in complex, expensive, and dangerous systems. Various methods, such as the Transfer function and State-Space Representation, can be used for system modeling. Theoretical aspects of the PID controller have been previously discussed as a practical experiment that can be conducted locally or remotely via the Internet. As a result, both the system as a whole and each unit have undergone mathematical modeling and analysis.


Figure 9. General System Block Diagram

Transfer function Representation was used to model the system in this paper because most universities with bachelor's degrees teach it to students, not State-Space Representation. The transfer function (TF) is the system's output and input relationship, as shown in Fig. 9 and Equation 1.

$$\boldsymbol{TFL(S)} = \frac{\boldsymbol{OUTPUT\ (S)}}{\boldsymbol{INPUT\ (S)}} \tag{1}$$

### 4.1. Encoder Sensor Modeling

In the system, two incremental encoders were utilized, one of which is a rotary encoder responsible for determining the pendulum's angle concerning the cart. To derive a transfer function for these sensors, it is essential to understand the properties of the sensor, as shown in Figure 10.

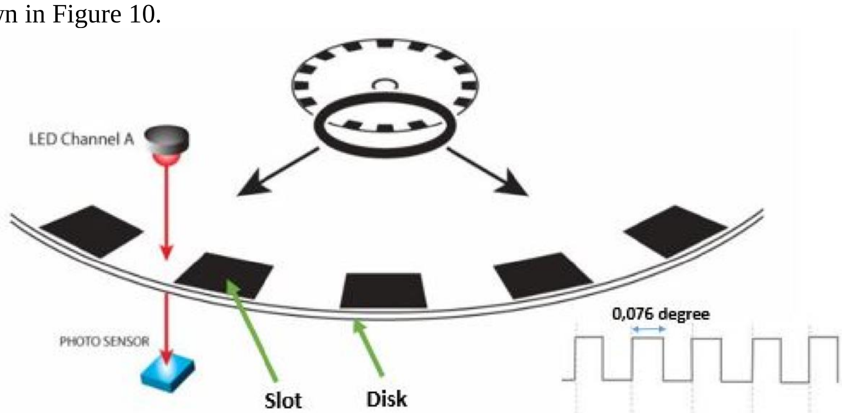


Figure 10. Incremental Rotary Encoder

The disk is divided into 5000 slots, and this means that when the pendulum is rotated at 0.072 degrees, the sensor will give one pulse as follows: 360 degrees/5000 slots = 0.072 deg/slot. The controller accounts for each falling and rising edge of the signal produced by the encoder sensor. The block diagram of the rotary encoder is shown in Fig 11. As mentioned before, TF is out/in. So, the TF of the incremental rotary encoder (TFR) is seen in Equation 2.

$$\boldsymbol{TFR(S)} = \frac{\boldsymbol{1}}{\boldsymbol{0.072}} = \boldsymbol{13.88} \tag{2}$$


Figure 11. Incremental Rotary Encoder Block Diagram

The other encoder is a linear encoder, which determines the linear motion or the cart's position on which the pendulum is installed. Moreover, the active length of the cart is 30 cm. It is a strip divided into 6000 slots as shown in Figure 12.

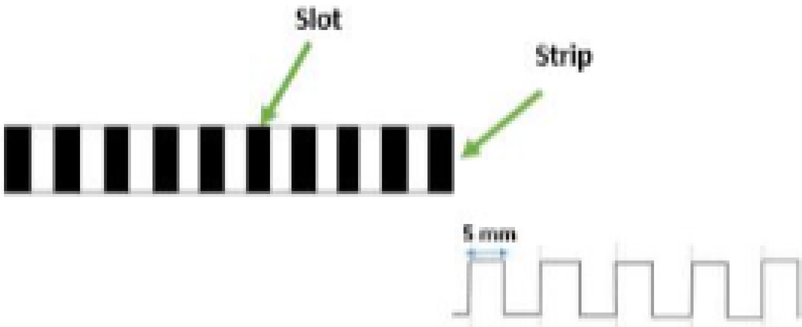


Figure 12. Incremental Linear Encoder

This means that when the cart moves 5 mm, the sensor will give one pulse: 30000 mm/6000 slots = 5 mm/slot. So, the TF of the incremental linear encoder (TFL) is seen in Equation 3. The controller accounts for each falling and rising edge of the signal produced by the encoder. The block diagram of the linear encoder is shown in Figure 13.

$$\boldsymbol{TFL(S) = \frac{1}{5mm} = 200} \tag{3}$$


Figure 13. Incremental Linear Encoder Block Diagram

### 4.2. Cart Modeling

The actual length of the cart, that is, the range in which the cart can move, is 30 cm, and the middle of the distance is the set point of linear movement as shown in Figure 14. That is, it is the location in which the cart is intended to achieve the optimal state of stability for the system. However, this is not the only condition for achieving the best equilibrium for the pendulum or the system. There is another condition that will be mentioned later. After the analysis of the free body diagram of the cart and converting all obtained equations by Laplace transformation, the transfer function of the cart is as seen in Equation 4.

$$\boldsymbol{TFcart\ (S) = \frac{\frac{(I+ml^2)s^2 - gml}{q}}{S^4 + \frac{b(I+ml^2)}{q}S^3 - \frac{(M+m)mgl}{q}S^2 - \frac{bmgl}{q}S}} \tag{4}$$

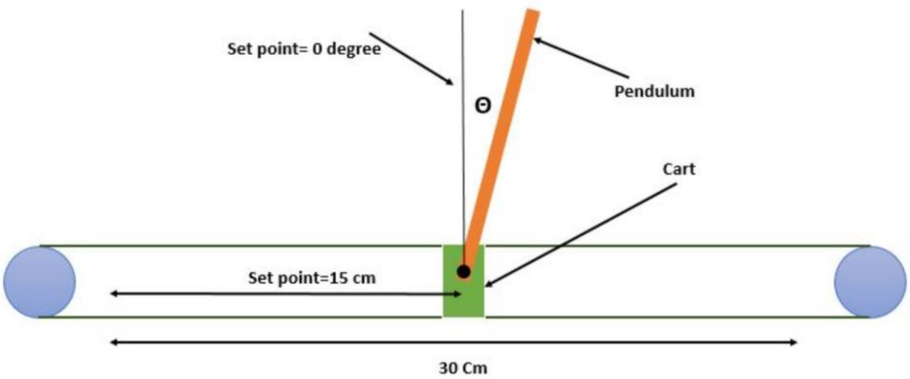


Figure 14. Cart and Pendulum Diagram

The set point of the cart is 15 cm, which means that the linear incremental encoder gives a pulse signal with 3000 falling and rising edges. So the set point equals 3000. So if it is supposed that the home of the cart is on the left side, the encoder equals 0, as shown in Fig. 14. When the encoder reads more than 3000, the cart should be moved from the left to the center. When the encoder reads less than 3000, the cart should be moved to the right to the center. All of them achieve the first condition of system stability. Fig. 15 shows the block diagram of the closed-loop system of the cart. Moreover, the transfer function of the cart closed loop system (TFc) is seen in Equation 5.

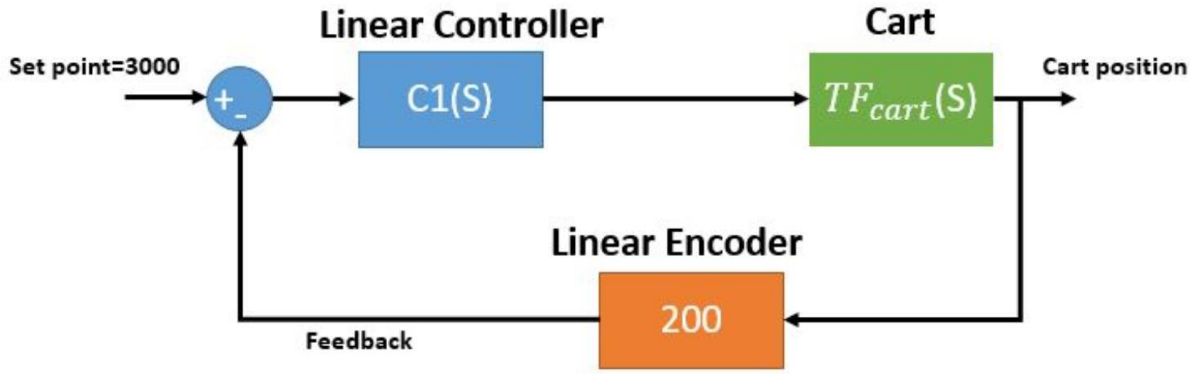


Figure 15. Closed Loop System of the Cart Block Diagram

$$TFc\ (S) = \frac{C1(S)TFcart\ (S)}{1\ + 200 * C1(S)TFcart\ (S)} \tag{5}$$

**4.3. Pendulum Modeling**

After the analysis of the free body diagram of the pendulum and the conversion of all equations obtained by Laplace transformation, the transfer function of the pendulum is seen in Equation 6.

$$TFpen\ (S) = \frac{\frac{ml}{q}S}{S^3 + \frac{b(M+m)mgl}{q}S^2 - \frac{bmgl}{q}} \tag{6}$$

All parameters of Equations 3 and 4 are illustrated in Table 1. As shown in Fig. 13, the set point of the pendulum is when theta equals 0 degrees, or the pendulum is vertical, which means that the linear incremental encoder gives a pulse signal with zero falling and rising edges. So, the set point equals 0. Before starting the experiment, the pendulum will be downward, and the value of the encoder will be assigned to be -2500. The set point equals 0. If the pendulum wobbles right, the cart moves left to set the pendulum to the set point or to be upward vertically, and so on. After that, the cart puts itself in the center to maintain the two conditions that achieve the perfect stability for the system overall. Fig. 16 shows the block diagram of the close-looped system of the pendulum. Moreover, the pendulum closed loop system (TFp) transfer function is seen in Equation 7.

$$TFp\ (S) = \frac{C2(S)TFpen\ (S)}{1\ + 13.88 * C2(S)TFpen\ (S)} \tag{7}$$

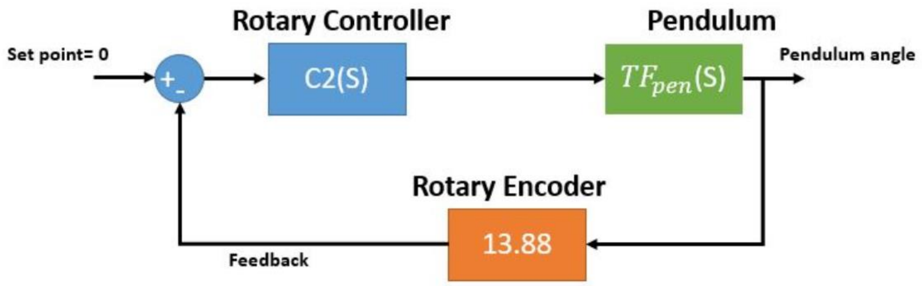


Figure 16. Closed Loop System of the Pendulum Block Diagram

Table 1. Parameters for Inverted Pendulum System

| Symbol | Variables and constants | Values |
|---|---|---|
| M | mass of the cart | 0.35kg |
| m | mass of the pendulum | 0.15kg |
| b | coefficient of friction for cart | 0.1 |
| l | length to pendulum center of mass | 0.2 m |
| L | mass moment of inertia of the pendulum | 0.006 kg.m2 |
| F | the force applied to the cart | DC motor force |
| X | cart position | x |
| theta | pendulum angle | theta degree |

### 4.4. Overall System Modeling

After analyzing the cart and pendulum and finding the transfer function for both, the closed loop overall system block diagram is shown in Figure 17.

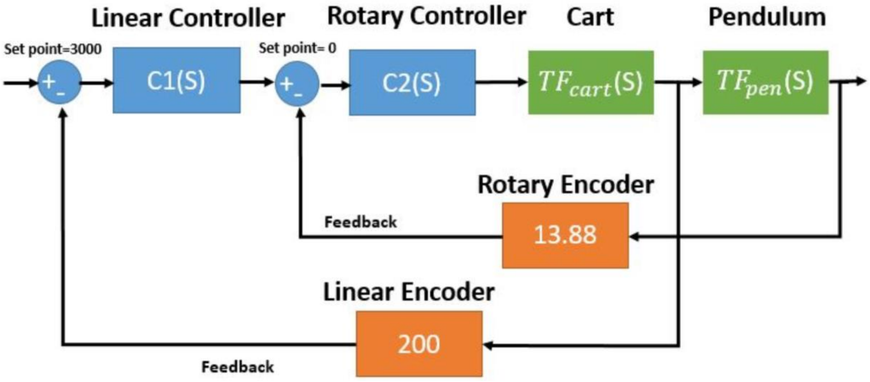


Figure 17. Overall System Block Diagram

After deducting and simplifying techniques on the system block diagram, the system transfer function is seen in Equation 8.

$$\mathbf{TFall(S)} = \frac{\mathbf{C1(S)C2(S)TFcart(S)TFpen(S)}}{\mathbf{1 + 13.88 * C2(S)TFcart(S)TFpen(S) + 200 * C1(S)C2(S)TFcart(S)}} \tag{8}$$

### 5. System Development

### 5.1. Mechanical Development

The inverted pendulum system was developed from the cart of an old HP laser jet printer with some modifications, such as adding the pendulum rod in the middle of the cart, which is driven by a DC motor, as shown in Figure 18, The pendulum was fixed on rotary bearings (8mm X 22mm X 7 mm). Moreover, an incremental rotary encoder (5000 sectors) was fixed with the pendulum to measure its angle with the cart. The cart was tied with a pulley (20 teeth GT2) and rubber belt (GT2), and two limit switches were set on the far right and left to give the PID controller limited scope of movement of the cart.

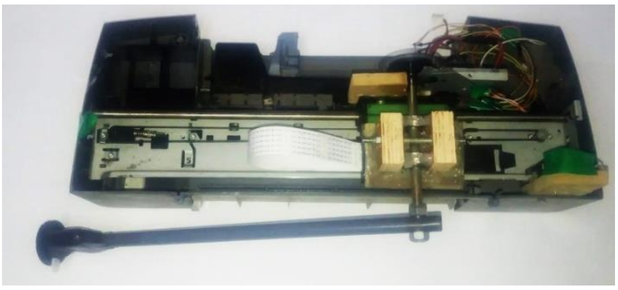

Figure 18. Cart Inverted-Pendulum Hardware

The motion of the cart moves linearly, and the pendulum rotates angularly. The system has two feedbacks, as shown in Figure 19. The Arduino code on the local NodeMcu controlled the experimental hardware.

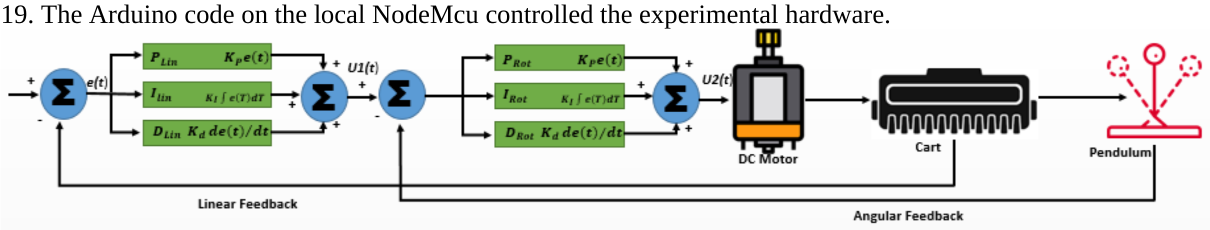


Figure 19. Feedback Control System of the Inverted Pendulum

### 5.2. Control System Development

The control software uses the Blynk platform, which has a built-in IoT cloud. There are two distinct areas: the lab and the student/user places. The experiment is set up in the lab using an inverted pendulum, NodeMCU, and an IP camera. The student/user place can be any location where students wish to experiment using a mobile device or computer via the Blynk and Skype platforms, as shown in Figure 20.

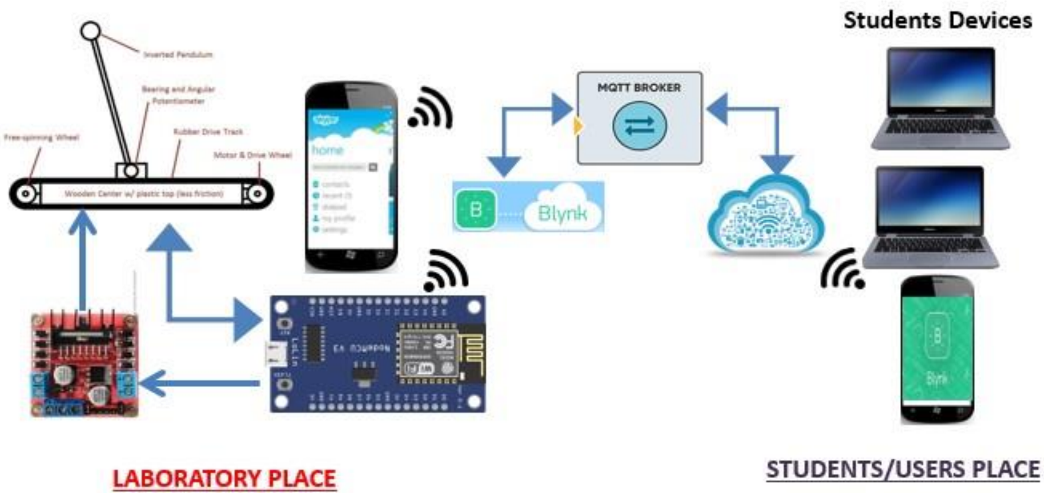


Figure 20. Schematic of the Developed Lab Experiment System

Generally, the system was built as described in Figure 21. The remote access devices connect with the local control NodeMcu via the Blynk cloud and receive experimental data from the cloud and video stream via Skype using video calls, which are set up to be an automatic response. Furthermore, the remote access device can send control data, such as PID tuning parameters, to the Blynk cloud via the internet and modify the stability of the inverted pendulum system to achieve the experiment's learning objectives. The NodeMCU controller performs the PID algorithm of the pendulum system by sending control signals to the cart motor and acquiring the position values from the encoders. The balance of this system needs feedback to adjust its state and position because there are two types of movement.

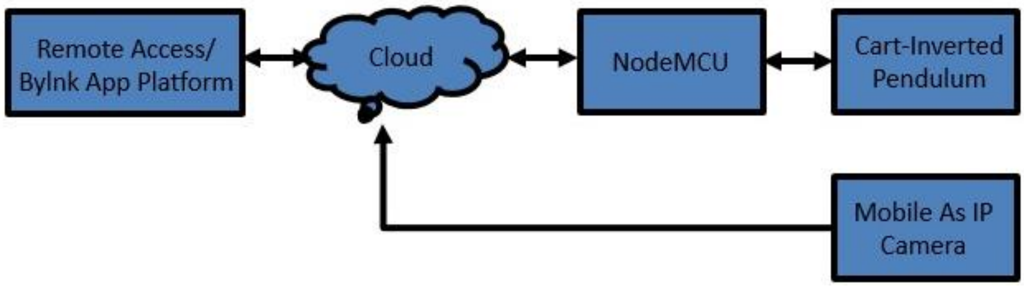


Figure 21. System General Control Layout

## 6. Conclusion and Future Works

This study demonstrates the increasing use of distance education, particularly during wars or epidemics, to ensure uninterrupted learning. The study focuses on designing and implementing a PID controller experiment using IoT in remote laboratories. A cart-inverted pendulum system was developed to enhance students' understanding of PID controller tuning in real-world contexts. Two controllers were implemented for system control and feedback. Integrating the Blynk platform allowed real-time visualization, PID parameter control, and video streaming. Remote connectivity was achieved through the NodeMcu IoT board, enabling data transmission to the cloud. Mathematical models were created for sensors and the system, facilitating theoretical and practical PID experiments. This setup enables local and remote access to the experiment, providing students an immersive learning experience.

Future work will focus on developing a dedicated web page seamlessly integrated with Firebase as a cloud platform and further linked to the university student portal. This progressive work aims to expand the range of experiments, encompassing endeavors like regulating DC motor speed and empowering students to generate experiment reports effortlessly. These reports will be conveniently transmitted to their instructors through an automated system, streamlining the feedback process.

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Authors declare that there is no conflict of interest regarding the publication of this paper.

**Ethical Approval**

It is declared that during the preparation process of this study, scientific and ethical principles were followed, and all the studies benefited from are stated in the bibliography.

**Availability of data and material**

Not applicable.

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