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A practical approach to teaching control engineering: design and implementation of a pneumatic levitation system with PID Control

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***Abstract*– Teaching control engineering to undergraduates often struggles to bridge the gap between theory and practice, leaving students with a poor understanding of how theoretical concepts apply to real-world systems. This research tackles this issue by designing and implementing a pneumatic levitation system as a teaching tool. The process involved selecting components like an Arduino, an ultrasonic sensor, and a fan, analyzing the system, building a prototype, and implementing a PID controller. An optimal control model based on the "skyhook" system was used to enhance performance. The completed system successfully levitated a sphere stably and accurately. Tests evaluated the PID controller's performance and how its parameters affected the system's response. This hands-on approach, using a pneumatic levitation system, provides a practical means of teaching control engineering, allowing students to experience theoretical concepts in action. This can improve their understanding and ability to design and implement control systems, enhancing engineering curricula and developing practical skills in future engineers.**

***Keywords*-- Control engineering, PID Control, Engineering Education, Curriculum Improvement.**

I. Introduction

Control engineering is a critical discipline that deals with the design and implementation of systems that can regulate the behavior of other systems or processes. It plays a vital role in various fields, including industrial automation, robotics, aerospace, and many others. At the undergraduate level, control engineering education aims to equip students with the fundamental knowledge and skills necessary to analyze, design, and implement control systems for diverse applications [1]. One of the essential aspects of control engineering education is to bridge the gap between theoretical concepts and practical implementation. Students often find it challenging to understand how the theoretical principles they learn in the classroom translate into real-world systems. This disconnects between theory and practice can hinder their ability to design effective control systems and appreciate the practical implications of control engineering concepts [2].

To address this challenge, there is a growing need for innovative teaching tools and methodologies that can provide students with hands-on experience in control system design and implementation [3]. Such tools should allow students to experiment with different control strategies, observe the behavior of real systems under various control parameters, and gain a deeper understanding of the interplay between theoretical concepts and practical considerations [4].

This study focuses on the development of a pneumatic levitation system as a practical tool for teaching control engineering. Pneumatic levitation is a fascinating phenomenon that involves suspending an object in the air using a stream of pressurized gas [5]. The system's behavior is governed by the principles of fluid mechanics, dynamics, and control theory, making it an ideal platform for demonstrating various control concepts [6].

The main objective of this thesis is to design and implement a pneumatic levitation system that can serve as an engaging and effective teaching tool for undergraduate control engineering education. This objective entails several key steps:

A. *System design: To design the mechanical, electrical, and electronic components of the pneumatic levitation system, including the selection of appropriate sensors, actuators, and control hardware.*
B. *Control System Implementation: To implement a PID (Proportional-Integral-Derivative) controller that can regulate the position of the levitating object.*
C. *Optimal Control Model Integration: To incorporate an optimal control model based on the "skyhook" system to enhance the performance and stability of the levitation system.*
D. *Experimental Validation: To conduct experiments to validate the performance of the implemented control system and assess its ability to achieve stable and accurate levitation.*

By providing students with a hands-on experience in designing, implementing, and testing a control system for pneumatic levitation, this thesis aims to enhance their understanding of control engineering concepts and foster their practical skills. The project also addresses the need for "Enhancing Undergraduate Education and Curriculum Improvement" by introducing an engaging and tangible learning experience that complements traditional teaching methods [7].

The use of physical systems as teaching tools in control engineering education has been explored in various studies. For instance, Fuertes Paucar [8] developed a temperature control module to provide students with hands-on experience in designing and implementing PID controllers. Meneses Morales and Zafra Siancas [9] designed a ball and beam system to illustrate the challenges of controlling nonlinear and unstable systems. Parra Quispe [10] investigated the design and implementation of industrial PID controllers, highlighting their applications in various control scenarios. Other researchers have explored the use of pneumatic levitation systems specifically for control education. Bello et al. [11] developed a robust pneumatic levitation plant for research and training in control and artificial vision. Hernández Miguel et al. [12] designed and implemented a pneumatic levitation system to test classical control algorithms.

These studies demonstrate the growing interest in using physical systems, including pneumatic levitation systems, as effective teaching tools in control engineering education. The present thesis builds upon these previous works by incorporating an optimal control model based on the "skyhook" system, further enhancing the educational value of the pneumatic levitation system [13] .

The pneumatic levitation system developed in this study offers several advantages as a teaching tool. It is a visually appealing and interactive system that can capture students' attention and curiosity. It allows students to observe the direct impact of control parameters on the system's behavior, providing a tangible demonstration of control concepts. Furthermore, the system's complexity can be adjusted to match the students' level of understanding, making it suitable for different stages of the undergraduate control engineering curriculum [14] .

This study contributes to the field of control engineering education by developing a practical and engaging teaching tool that bridges the gap between theory and practice [15] . The pneumatic levitation system, along with the implemented PID controller and optimal control model, provides students with a hands-on learning experience that can enhance their understanding of control concepts and foster their practical skills [16] . This research aligns with the broader goal of improving undergraduate education and curriculum by introducing innovative teaching methodologies that complement traditional classroom instruction.

II. METHODOLOGY

This research followed a structured approach to design, implement, and evaluate a pneumatic levitation system for enhancing control engineering education. The methodology comprised the following key stages [17] :

A. *Problem analysis and requirements identification*

The initial step involved a thorough analysis of the challenges encountered in teaching control engineering at the undergraduate level. This included a review of existing teaching methodologies, available laboratory equipment, and the learning outcomes expected of students. Based on this analysis, specific requirements for the pneumatic levitation system were identified, considering factors such as cost-effectiveness, ease of implementation, portability, and the ability to demonstrate key control engineering concepts.

B. *System design and component selection*

The next stage focused on designing the pneumatic levitation system. This encompassed the mechanical design of the system's structure, ensuring stability and appropriate dimensions for the levitating object. The electrical and electronic design involved selecting suitable components, including an Arduino microcontroller for control, an ultrasonic sensor for measuring the object's position, and a fan for generating the airflow. The selection criteria for these components were based on their compatibility with the Arduino platform, performance characteristics, cost-effectiveness, and availability.

C. *Control system development*

A crucial part of the methodology involved developing the control system for the pneumatic levitation system. This entailed implementing a PID controller to regulate the position of the levitating object. The PID controller parameters were carefully tuned to achieve stable and accurate levitation. Additionally, an optimal control model based on the "skyhook" system was incorporated to further enhance the system's performance and stability.

D. *Prototype construction and testing*

Following the design and control system development, a prototype of the pneumatic levitation system was constructed. The construction process involved assembling the mechanical structure, integrating the electronic components, and ensuring the proper functioning of all parts [18] . Rigorous testing was then conducted to evaluate the system's performance under various conditions. This included assessing the stability of the levitation, the accuracy of the position control, and the response of the system to disturbances, see fig. 1.

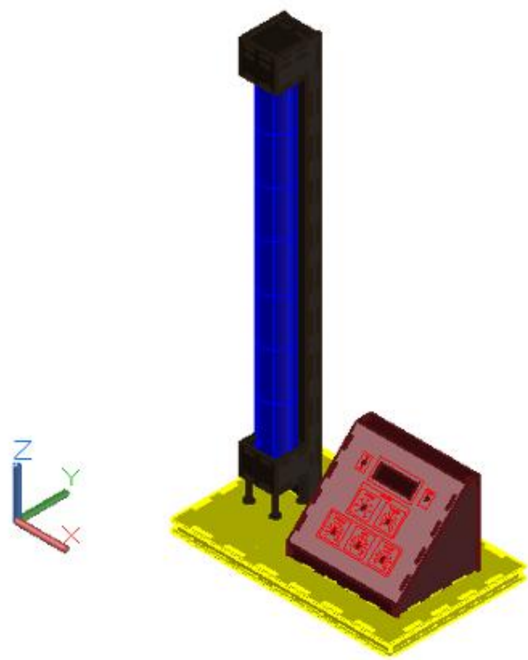

Fig. 1 Overview of the pneumatic levitation module

Figure 1 consists of three main parts:

- Base - support: The base unifies the different parts, provides support for the internal elements of the Human-Machine Interface (HMI), and acts as a point of support for the tube-sphere system, see fig 2.

- Human-Machine Interface (HMI): This includes the five input elements and one output element of the HMI, the HMI includes five input controls for adjusting parameters, as well as a space for the output element (LCD display). Additionally, there are two slots for the on/off switch to the left of the display and a reset button on the right, see fig. 3.
- Tube-sphere system: This features a tube with a length of 600 mm for the sphere to travel within. The tube has a diameter of 54 mm, while the sphere has a diameter of 51.19 mm, ensuring sufficient clearance for the sphere to move freely from one end of the tube to the other, see fig. 4,5.

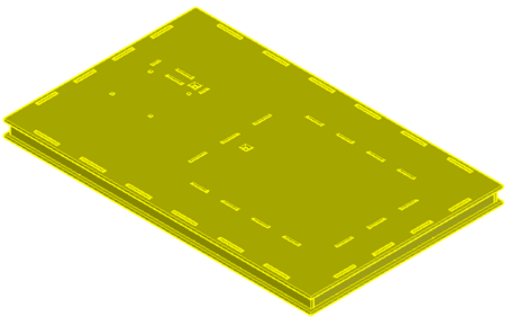

Fig. 2 View of the pneumatic levitation module support base

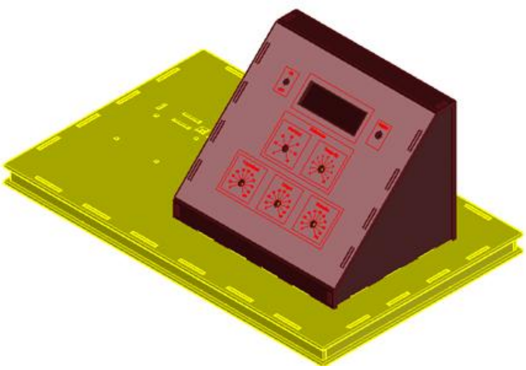

Fig. 3 HMI view of the pneumatic levitation module

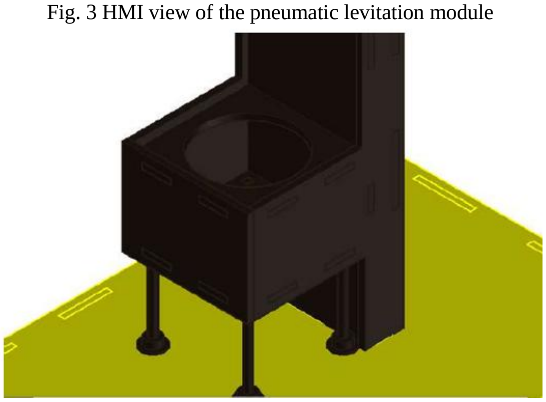

Fig. 4 View of the bottom of the tube-sphere system

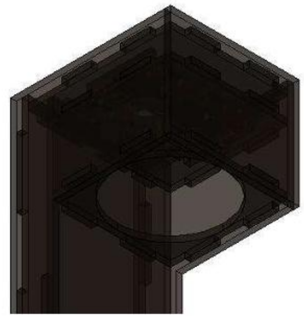

Fig. 5 Top view of the tube-sphere system

D. *Electronic design*

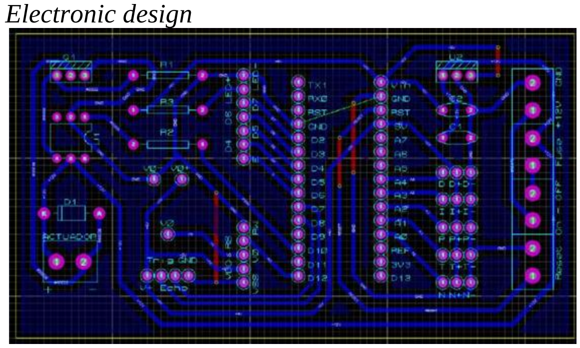

Fig. 6 View of the components and tracks of the electronic board

Fig 6 shows the electronic components will be arranged on a single board, which must accommodate all the necessary components to ensure the proper operation of the devices used. The board has an area of 102.87 x 55.88 mm. It can be divided into three sections, from left to right: electronic components for the output elements, the Arduino, and electronic components for the input elements.

Table 1 shows the electronic components are detailed in the following tables:

TABLE I

ELECTRONIC COMPONENTS ARE DETAILED IN THE FOLLOWING TABLES

Components	Electronic device
C1	0.33uF capacitor
C2	0.1uF capacitor
D1	1N4004 Diode
Q1	Mosfet IRFZ44N
R1	10kΩ resistor
R2	220Ω resistor
R3	220Ω resistor
U1	4N35 Optocoupler
U2	Regulator 7806
Terminals V0-, V0 and V0+	10kΩ Trimpot

D. *Performance evaluation and analysis*

The final stage of the methodology involved evaluating the overall performance of the pneumatic levitation system. This included analyzing the experimental results, comparing the system's behavior to theoretical models, and assessing the effectiveness of the PID controller and the "skyhook" optimal control model [19]. The evaluation also considered the system's suitability as a teaching tool, taking into account factors such as ease of use, clarity in demonstrating control concepts, and potential for student engagement, see fig 7 prototype built.

Fig. 7 Pneumatic levitation prototype implemented

III. Results and Testing

To identify the system, a sampling process is conducted that considers both the input and output of the system. Due to the unstable nature of the system, a maximum input value is applied for 200 cycles. After the 200 cycles, a random signal with a change frequency of 3 cycles is applied for the following 300 cycles. Subsequently, the change frequency of the input is varied to 10 cycles for the remaining 500 cycles. With the input and output data, the state spaces and the transfer function can be identified.

The state-space matrices can be identified as shown in Table II.

TABLE II
Calculated and Identified State Matrices

Computed state matrix	Identified state matrix
$A=\begin{bmatrix}-l & l & 0\\ 0 & n & 0\\ 0 & 0 & p\end{bmatrix}$	$A=\begin{bmatrix}0.9977 & 0.02391 & -0.005914\\ 0.007252 & 0.1407 & -0.8469\\ 0.002981 & 0.6122 & 0.5149\end{bmatrix}$
$B=\begin{bmatrix}0\\ q\\ 0\end{bmatrix}$	$B=\begin{bmatrix}1.129x10^{-6}\\ 0.00122\\ -0.0002788\end{bmatrix}$
$C=[1 \quad 0 \quad 0]$	$C=[581.7 \quad -3.79 \quad 3.501]$
$D=0$	$D=0$

Using Matlab and the validated state-space representations, the transfer function can be calculated. This allows for the derivation of the discretized transfer function with a sampling period of 0.1 seconds.

Applying a step input to both the continuous and discrete models yields the following graphs:

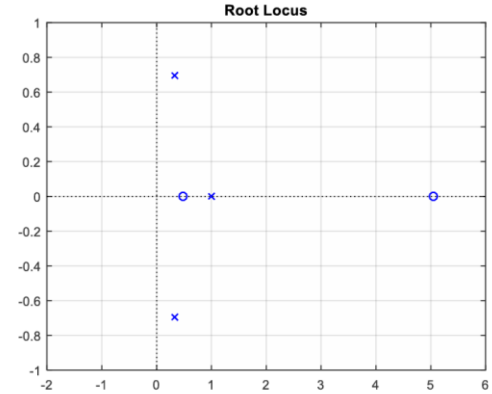

Fig. 8 Poles and zeroes of the identified model

For a discretization period of 0.1, zooming in on the overshoot region, this behavior can be observed.

Applying the input signal that was used to identify the system to the identified system, a behavior close to the measured one is obtained. With the tests carried out and the results shown in Figure 9, the system model can be considered valid [20].

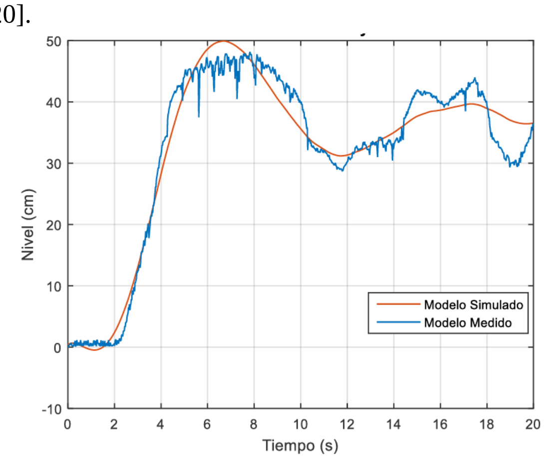

Fig. 9 Measured model and simulated model

C. Control Model

The block diagram in the Laplace domain. Below is the block diagram in the control system in the time domain:

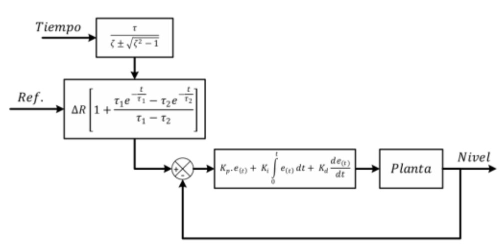

Fig. 10 Measured model and simulated model

Figure 10 is a control model that utilizes a PID (Proportional-Integral-Derivative) controller to regulate the plant's level. The reference signal is compared with the feedback from the plant's level to generate an error signal. This error signal is processed through the PID controller, which calculates the proportional, integral, and derivative actions. The output of the PID controller is added to a "bias" signal or correction factor, which compensates for system nonlinearities, and is sent as an input to the plant. Finally, the plant's level is fed back to close the control loop. Additionally, a time block is included, introducing a delay in the reference signal, and a filter that acts as an observer for the level variable.

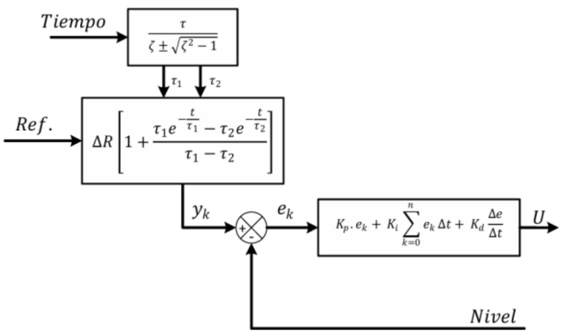

Fig. 11 Measured model and simulated model

Figure 11 represents a discrete control system for regulating the "Nivel" (Level). Note how the "Ref." (reference) signal is first modified by a block that introduces a "Tiempo" (Time) delay, likely to model the temporal behavior of the system. Then, the modified signal is compared with the output "yk" (current level) to generate an error "ek". This error feeds a discrete PID controller, whose proportional (Kp), integral (Ki), and derivative (Kd) gains determine the system response [21]. The controller output "Uk" finally acts on the "Nivel" block, which represents the dynamics of the process being controlled. The feedback loop from "Nivel" to the comparison with "Ref." closes the control loop, allowing the system to continuously adjust its output to reach the desired level.

D. *Testing*

With the control logic defined, testing proceeded on the physical system. Tests were conducted with controlled reference variations. For Kff equal to 0.1, the response did not approach the optimal response [22], see figure 12.

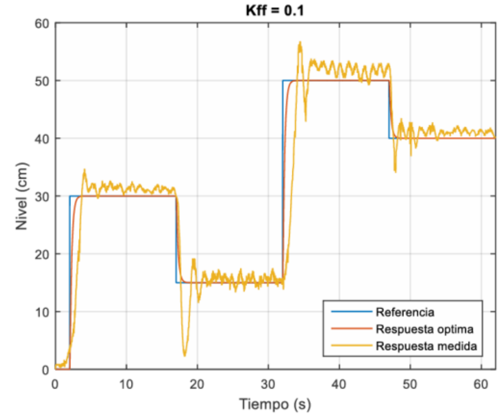

Fig. 12 Kff equal to 0.1

For a Kff value equal to 0.3, the response is close to the optimal model but exhibits abrupt changes in the response, see figure 13.

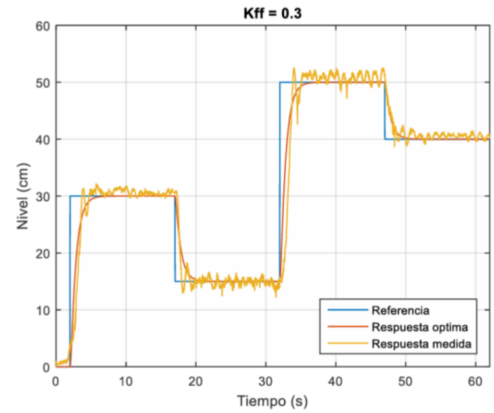

Fig. 13 Kff equal to 0.3

For a value of Kff = 1

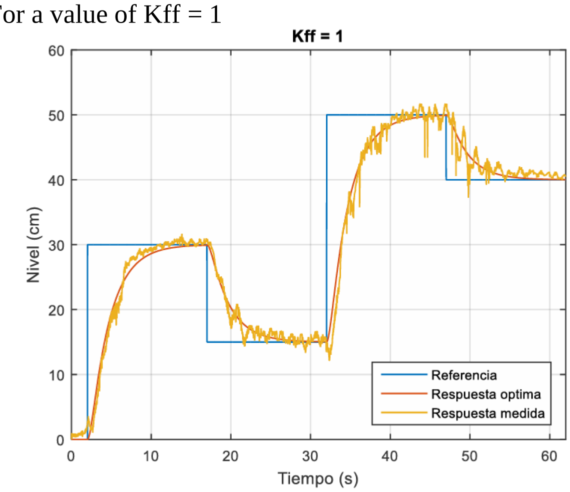

Fig. 14 Kff equal to 1

III. Discussion of Results

The implementation of the module included the design of an HMI that allows entering the 5 control variables (2 reference variables and 3 PID control constants). These variables generate changes in the dynamics of the system.

The development of the PID control was analyzed from a discrete point of view, and in the time domain, due to the selected controller (Arduino).

The flow diagram and the block diagram are reflected in the Arduino code that was implemented, showing a direct relationship between theory and practice, given that the block diagram processes are supported in result and testing chapter.

IV. Conclusions

- The design of the system structure allows control variables to be entered, and due to the characteristics of the system, changes in control variables are more clearly perceived.

- The Skyhook-Damper model is compatible with the tube-sphere levitation system. As the model is second order, the solutions were determined, and the response curve could be represented in the time domain.

- The control logic was determined with a discretization factor for PID control because the control element was an Arduino.

- The optimal model analysis was performed in the time domain since the control peripherals work in the temporal domain.

- Each element of the implemented control can be explained directly with the analysis carried out, thus generating a direct link between the theory and the implementation of the controller for the tube-sphere system.

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