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Cyber-Physical Laboratory Station for Thermal Fluids Online Experiments

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Abstract– This paper presents the design, implementation, and evaluation of a cyber-physical laboratory station for thermal fluids online experiments. The system integrates advanced remote-control technologies using a structured methodology to create an accessible and practical learning environment for engineering education. It leverages state-of-the-art hardware, including NI-myRIO, industrial controllers, and relay modules, along with software solutions based on LabVIEW and MQTT. The station enables real-time control and precise data acquisition in a remote setting. A detailed Piping and Instrumentation Diagram (P&ID) and a modular control unit form the backbone of the system, ensuring accurate monitoring and regulation of thermal and flow variables. The laboratory station is integrated with the RemoteLabo platform, which utilizes computational notebooks to provide seamless remote access. This integration allows students to perform experiments simulating realistic thermal processes, reinforcing theoretical concepts in heat transfer and fluid dynamics. Extensive experimental evaluations were conducted to verify system performance. Sensor calibration procedures, including controlled thermal baths for RTD sensors and calibrated electronic devices for flow measurements, confirmed data reliability. The performance of various heat exchangers was assessed under controlled conditions, demonstrating effective thermal regulation and the attainment of steady-state operation. The experimental results highlight the system's capability to support remote experimentation while maintaining high accuracy and reproducibility. This study advances remote laboratory technologies and provides a scalable framework for practical training in thermal fluids engineering. The findings contribute to improving engineering education by enabling realistic, high-fidelity experimentation.

Keywords-- Thermal Fluids, Cyber-Physical Systems, Remote Laboratories, NI-myRIO, LabVIEW, MQTT, Online Experiments.

I. INTRODUCTION

The design and implementation of laboratory stations in engineering and science education face multiple challenges, notably the fundamental role of the laboratory in the educational process. Multiple studies [1], [2], [3] highlight that laboratories not only facilitate hands-on experiences and the application of engineering principles, but also require precise alignment between experimental activities and learning objectives to achieve educational goals. The effectiveness of remote laboratories and simulations has emerged as a critical area of study. In [4], a model is proposed that guides the design and evaluation of these distance learning environments, emphasizing the need to develop laboratory stations that can be effectively integrated into remote platforms. The complexity is further heightened when considering the remote control of the laboratory station [5]. Aspects such as communications, instrumentation, and control must be carefully addressed, as their implementation can vary significantly depending on the field of knowledge. In this regard, [6] describes the process of creating a remote laboratory for engineering education, emphasizing the importance of selecting appropriate technologies, ensuring robust connectivity, and designing intuitive user interfaces.

The development of complex remote learning laboratories requires meticulous planning. In works such as [7], an integrated methodology is proposed that details the necessary stages for establishing a remote access system, highlighting critical factors such as security, scalability, and user experience. This systematic approach is essential to overcome the challenges inherent in the virtualization of laboratory educational environments.

The present study aims to develop and implement a thermal fluids laboratory station that will be remotely controlled via the RemoteLabo platform [5], an online laboratory developed by the Universidad Politécnica de Madrid in collaboration with the Universidad de Guayaquil. This initiative is designed to enhance the practical training of engineering students and researchers. The laboratory bench will enable the direct application of theoretical concepts in heat transfer and fluid dynamics by providing a controlled environment for conducting remote experiments. This station facilitates the practical application of engineering theories and principles through controlled experiments that allow students to observe and analyze heat transfer phenomena and fluid behavior. The laboratory station will integrate, in a multidisciplinary manner, concepts from thermodynamics, fluid mechanics, and industrial control, using advanced technologies such as NI-myRIO, LabVIEW, and IoT communication protocols (MQTT). This integration optimizes the teaching-learning process in engineering, permits the reconfiguration of the remote laboratory system based on pedagogical needs, and facilitates the acquisition of technical skills in an online laboratory.

The document is organized as follows: Section I, Methodology, explains the steps followed in the design and implementation of the proposal; Section II evaluates the results obtained; and Section III presents the conclusions, analyzing the results achieved.

II. METHODOLOGY

For the development and implementation of the laboratory station, a structured methodology was employed, executed in several key stages, Fig.1. Based on previous works [4], [8] that focus on the development of remote laboratories integrated into learning management systems, an initial analysis and definition of requirements was conducted. This phase established the station's specific requirements by focusing on the desired objectives and competencies, accompanied by a detailed analysis of the related course content. Based on these identified requirements, the design of the experiments to be implemented in the station was developed. This phase included a precise determination of the type of hardware and software necessary for the effective execution of the planned experiments. Once the experiments and requirements were defined, the process moved on to the selection and development of the hardware and software, involving the choice and creation of the appropriate devices and programs to realize the essential components for implementing the remote laboratory. Consequently, the system was integrated and exhaustive tests were conducted to improve and rectify any potential errors, ensuring the functionality and reliability of the laboratory station while also laying the groundwork for future enhancements.

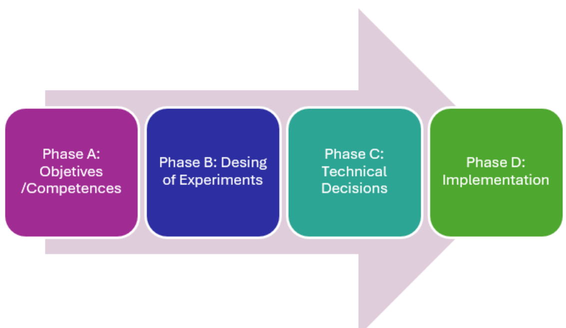

Fig. 1 Phases of the Design and Development of the Laboratory Station.

A. Determination of Requirements and Experimental Design of the Thermal Fluids Laboratory

To establish the requirements for the Thermal Fluids laboratory station, a detailed analysis of the desired educational objectives and competencies was conducted. This process considered the multifunctionality of laboratories in engineering education, highlighting key aspects such as the improvement of knowledge and practical skills [1], [9], the promotion of critical thinking and problem solving [10], [11], the application of theoretical concepts [12], [13], the development of teamwork [14], [15], the strengthening of laboratory technical skills [5], [16], [17], the promotion of research and inquiry [1], [18], and the inclusion of ethical and sustainable practices [19]. The academic content of subjects related to the Thermal Fluids laboratory was analyzed at the Faculty of Mathematical and Physical Sciences of the Universidad de Guayaquil and the Higher School of Industrial Engineers at the Universidad Politécnica de Madrid. The reference courses include "Industrial Processes" and "Industrial Heating and Cooling," which cover the fundamentals of heat transfer, thermal exchangers, and thermal management in industry. These courses are designed to develop skills in evaluating and optimizing thermal systems, as well as applying knowledge in real industrial scenarios. Based on the academic content, six laboratory practices were designed aimed at understanding heat transfer and optimizing thermal systems. These practices include the study of different types of heat exchangers and their industrial applications, the comparison of efficiency in parallel and counterflow configurations, the evaluation of the impact of flow rate on heat transfer and the calculation of the Reynolds number, the determination of the average heat transfer coefficient and its relevance in exchanger design, energy balance and the quantification of energy losses, and the determination of efficiency using the NTU method and its comparison across different types of exchangers. The objectives of the laboratory are designed to develop both practical and theoretical skills in thermal fluids engineering. The goal is to facilitate the application of theories in real environments, provide direct experience in the analysis and operation of heat exchangers, foster the development of experimental and analytical skills, integrate multidisciplinary knowledge from thermodynamics, fluid mechanics, and heat transfer, prepare students for professional practice in thermal engineering, promote research and innovation in thermal fluids management, and emphasize safety and sustainability in the design and operation of thermal systems. The design of the laboratory station was carried out based on previous studies and current regulations [20], [21].

B. Development of the P&ID for the Thermal Fluids Laboratory Station

The design and implementation of the educational laboratory station requires the development of a Piping and Instrumentation Diagram (P&ID) following established methodologies [22]. This process begins with the creation of a Block Flow Diagram (BFD), which provides a schematic and simplified representation of the process, highlighting the main material flows and facilitating the understanding of the interactions among the different system components. Subsequently, a Process Flow Diagram (PFD) Fig.2 is developed, serving as a preliminary project planning document that offers a higher level of detail compared to the BFD, with a focus on the key elements of the system. While the BFD and PFD emphasize the principal components of the plant, the P&ID provides a detailed description of all elements involved in the installation.

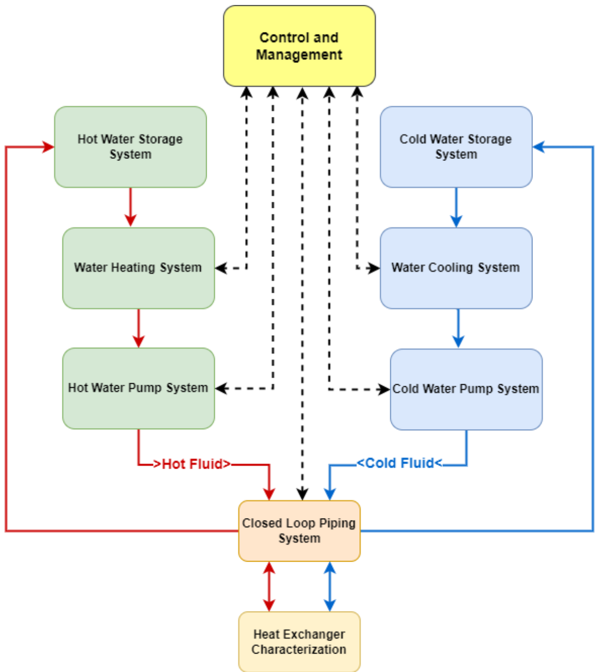

Fig. 2 Lab Station Block Flow Diagram (BFD).

Within the design of the laboratory station, the goal is to evaluate the thermal performance of various heat exchangers using water as the working fluid in a single-phase regime. For this evaluation, fundamental parameters such as flow rates and the inlet and outlet temperatures of the exchangers will be measured. The proposed installation is composed of several interconnected functional blocks that ensure the proper operation of the system.

The Water Storage System is crucial for preserving the working fluid in its original thermal conditions throughout the heating and cooling processes. The Cooling and Heating System regulates the water temperature, enabling the analysis of heat exchangers under different thermal gradients. For fluid transport, a Closed Circuit Piping System is implemented, which, through the use of valves, allows the modification of flow direction according to experimental needs. Additionally, the station incorporates four types of Heat Exchangers, whose performance will be characterized under different operating scenarios. These fluids are driven through the system by two Water Pumps, one designated for hot water and the other for cold water. Finally, the Control and Management System supervises and regulates all operations, ensuring automation and precision in the collection of experimental data.

The Process Flow Diagram (PFD) of the station illustrates the key components of the system and serves as the basis for the development of the P&ID. In this diagram, the essential elements are detailed, including various types of heat exchangers (shell and tube, plate, concentric), storage tanks for hot and cold fluids, water pumps, a cooling system, and servo-actuated valves. Additionally, a detailed description of each component with its respective identifier is provided, allowing for a better understanding of the operation of the installation.

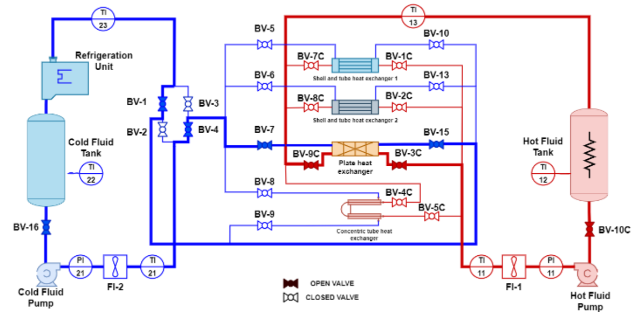

Fig. 3 Thermal Fluids Lab Station P&ID

As a result of the more detailed design process, a Piping and Instrumentation Diagram (P&ID) Fig.3 was produced, providing a comprehensive view of the instrumentation and piping necessary for the operation of the laboratory station. This diagram enables the complete integration of the different system components into a functional experimental environment, ensuring that all measurements and controls are carried out in a precise and reliable manner.

C. Implementation of Thermal Fluids Laboratory Station System

The developed laboratory station Fig. 4 is composed of two main functional blocks. The first is the Control Unit, which is responsible for managing, controlling, and communicating within the laboratory station. The second is the Service Unit, which integrates the necessary equipment for the thermal fluids installation. The figure illustrates the detailed design of the installation and the functional diagram of both blocks, whose characteristics and specifications are explained in detail in the following sections.

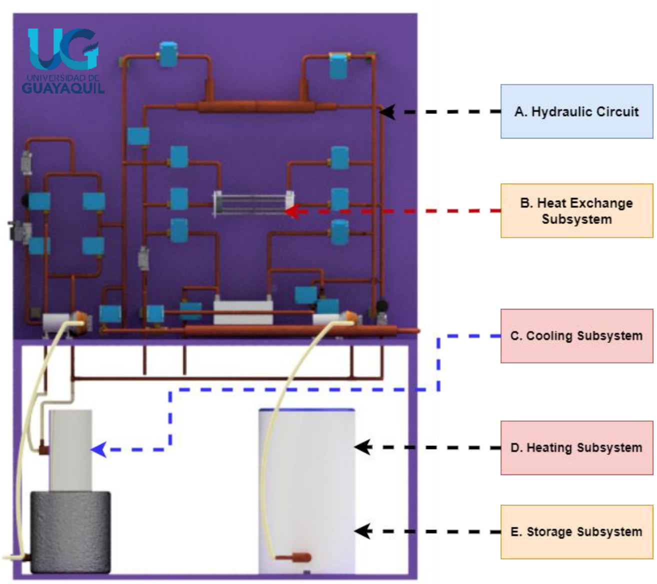

Fig. 4 Lab Station implementation of the functional block

The Laboratory Control Unit is responsible for supervising the experiments, instrumentation, and industrial communication of the various components of the station. Its functions include controlling experimental processes through embedded systems and electronic controllers, collecting and conditioning sensor signals to ensure accurate measurements, and managing the industrial communications that allow interaction between the laboratory devices and remote users. Additionally, this unit integrates the power supplies necessary for the operation of the electronic devices.

Each component of the Control Unit has been selected with the goal of optimizing system performance and efficiency. Key devices include an Industrial Ethernet Switch, responsible for communication among the various laboratory elements; the NI-MyRIO Fig. 5, an embedded RT system used for data acquisition and control with multiple analog and digital inputs and outputs; and the CN-730 Temperature Controller, designed to handle RTD sensors and facilitate integration into industrial systems via the MODBUS RS-485 protocol.

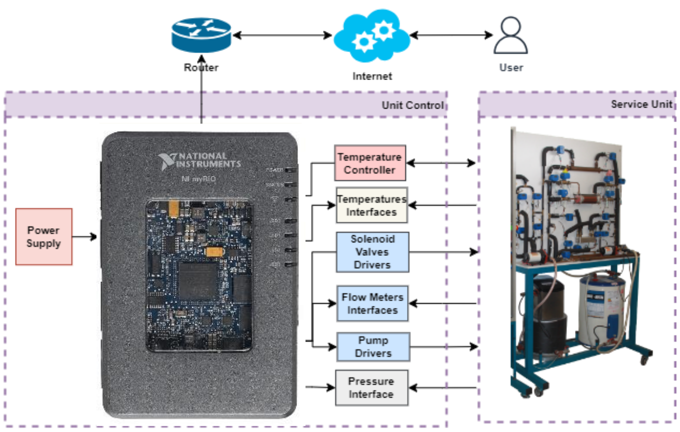

Fig. 5 Diagram of the Electronic Controllers and Transmitters Implementation in the Control Unit

Furthermore, the unit includes Relay Modules for Solenoid Valves, which enable the automation of valves through high-capacity relays, and Pump Controllers, designed to operate DC pumps with pulse-width modulation (PWM) regulation. To ensure the correct conversion and reading of temperature signals, PT100 Signal Conditioners are integrated, based on the MAX31865 converter, allowing for precise conversion of RTD signals to digital format. Finally, the industrial power supply provides standard voltages of 12V and 24V, ensuring system stability and the continuous operation of the equipment.

Based on this infrastructure, the thermal fluids laboratory provides an efficient remote experimentation environment, allowing for the precise monitoring and control of thermal and flow variables, while ensuring stable and reliable communication with users accessing the remote experimentation platform.

D. Real-time Control Architecture and Data Acquisition of the Thermal Fluids Laboratory Station

Considering that the control of the laboratory station is based on NI-myRIO technology, an embedded computer used in the development of real-time (RT) systems, its main feature is the use of the graphical programming language LabVIEW. This enables parallel processing and hardware interaction through a reconfigurable input/output architecture. This combination facilitates integration with cloud technologies, allowing for real-time remote experiments. The main features of the proposed architecture with this device include:

1) *Deterministic Control:* Algorithms executed in parallel on the myRIO's real-time processor.
2) *RIO Scan Interface:* Allows updates of input/output variables without the need for FPGA programming.
3) *IoT Communication:* Integration with MQTT for interaction with IoT applications.
4) *Industrial Communications:* Support for protocols such as SPI and Modbus RTU, enabling integration with sensors, motor controllers, and data acquisition systems.

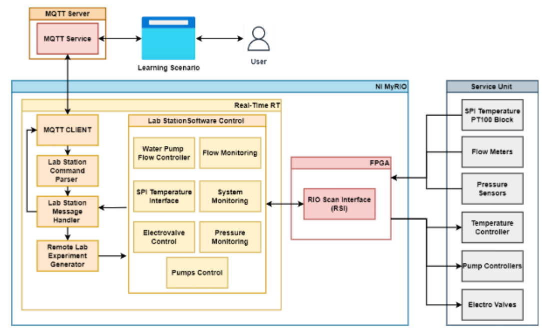

Fig.6 LabVIEW Real-Time Control Software Architecture

The software is developed based on a producer-consumer architecture Fig.6 to optimize data management and control. Information is acquired in the FPGA, transmitted to the real-time processor, and managed through modular architecture with MQTT clients and other services to handle communication.

III INTEGRATION AND EVALUATION OF THE LABORATORY STATION

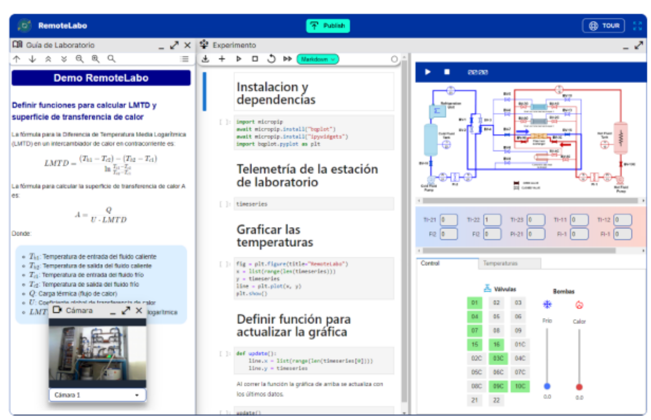

Fig.7 RemoteLabo Online Laboratory System

For the evaluation and integration of the various components of the test bench station, the system was connected to the RemoteLabo platform Fig.7, an online laboratory that utilizes computational notebooks. Both the control unit and the functional unit of the test bench were integrated, and the performance and efficiency of the station's heat exchangers were assessed.

Sensor calibration was performed using a streamlined procedure. For RTD temperature sensors, a controlled thermal bath was employed, with readings compared against a reference thermometer and adjustments made in the LabVIEW software when discrepancies were detected. Calibrated electronic devices were used to verify flow meter measurements. Pressure measurements could not be confirmed due to the absence of standard manometers; this limitation is expected to be addressed in future work. Temperature control of the hot water tank was managed by a calibrated industrial controller, and the DC pumps were operated via a PWM controller. The procedure to evaluate the performance of the heat exchangers began with the verification and calibration of the equipment. The initial temperatures of the tanks were set, and the heating and cooling system was activated. The exchanger was left until it reached a steady state, defined by temperature variations of less than ±0.5 ºK and mass flow variations of less than ±1.5%. Data was then collected for at least 300 seconds, recording inlet and outlet temperatures, mass flow rates, and differential pressure when applicable. The sampling frequency of the real-time embedded control system was configured to capture relevant fluctuations and maintain stability in flows and temperatures. for a few seconds.

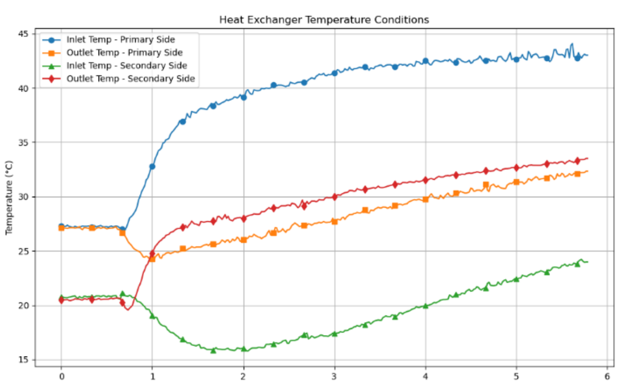

Fig.8 Experimental Data for the Characterization of Heat Exchangers

A. *Calculation of Heat Exchanger Performance*

During testing, the primary side inlet temperature of the exchanger was 35.21 °C and the outlet temperature was 24.79 °C. The logarithmic mean temperature difference (LMTD) was calculated to be 29.69 °C, which reflects good thermal performance. The average inlet and outlet temperatures on the primary side were determined using the formulas:

$$T\_av1 = (T\_11 + T\_12) \quad (1)$$

$$T\_av2 = (T\_21 + T\_22) / 2 \quad (2)$$

resulting in T_av1 = 35.21 °C and T_av2 = 24.79 °C.

The LMTD was computed as:

$$\Delta T\_lm = (\Delta T\_inlet - \Delta T\_outlet) / \ln(\Delta T\_inlet / \Delta T\_outlet) \quad (3)$$

yielding a value of 29.70 °C.

The results were verified using a thermal camera Fig.9 , which revealed a temperature gradient in the plate exchanger. In the counterflow configuration, the hot and cold fluids circulate in opposite directions, creating a distinct temperature gradient.

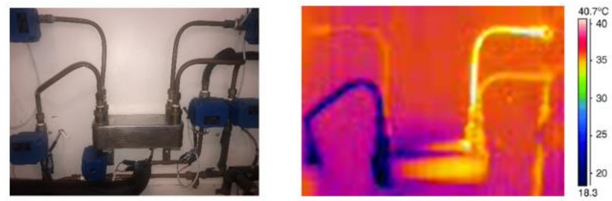

Fig.9 Thermal imaging of counterflow plate exchanger temperature gradient

The results shown in Fig. 10 demonstrate the direct correlation between the increase in the hot water flow rate and the rise in the coefficient (*U*), indicating a more effective heat transfer with higher flows. This not only confirms the foregoing but also validates the operational capability of the plate heat exchanger under the established test conditions.

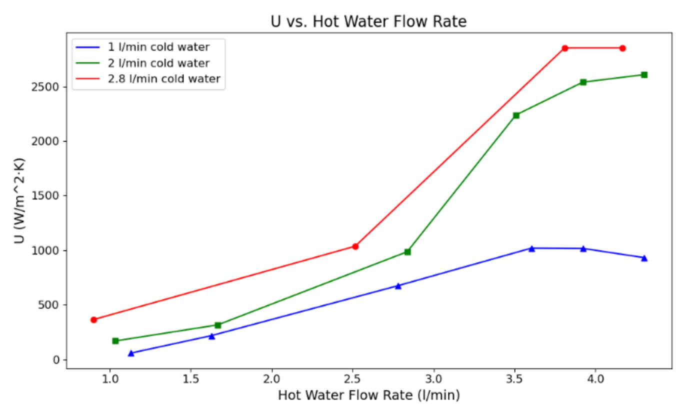

Fig.10 Graph of the Overall Heat Transfer Coefficient vs. Hot Water Flow Rate for Plate Heat Exchangers

IV. CONCLUSIONS

The study's conclusions demonstrate that a remote-controlled thermal fluids laboratory station was successfully developed and implemented, integrating hardware (such as NI-myRIO, industrial controllers, and relay modules) with software (LabVIEW and MQTT) to ensure stable and precise operation. The structured methodology from requirements definition and experimental design to the integration of a detailed P&ID effectively met the educational and technical objectives. Additionally, experimental validation through sensor calibration and the evaluation of heat exchanger performance confirmed the system's effectiveness in simulating real conditions and obtaining reliable data. Moreover, integration with the RemoteLabo platform highlights the viability of remote learning environments by facilitating real-time experimentation and promoting the development of practical engineering skills. Overall, these results underscore the study's contribution to advancing remote laboratories, emphasizing the system's adaptability, reliability, and potential for scalability.

Future work will focus on conducting additional experimental practices and implementing improvements in the program's architecture to integrate embedded devices such as Arduinos. These enhancements are expected to expand the laboratory's functionality by incorporating low-cost, flexible technologies that support innovative remote learning environments. By broadening the range of available tools and experiments, the project aims to further enrich the educational experience and better address the evolving needs of engineering training.

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