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ProtoCalib: Interactive Kit for Sensor Monitoring and Evaluation in Educational IoT Environments

ProtoCalib: Kit interactivo para monitoreo y evaluación de sensores en entornos IoT educativos

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Abstract: This paper presents ProtoCalib, a modular and interactive kit designed for the monitoring, calibration, and evaluation of sensors in educational environments based on the Internet of Things (IoT). The proposal addresses the need to strengthen practical engineering training through accessible, replicable, and connected tools, integrating elements of hybrid simulation and rapid prototyping. The system supports multiple categories of sensors (temperature, gases, angle, distance, contact, speed, and color/light) and is structured in independent modules connected to an ESP32 platform programmed in MicroPython, linked to a desktop application developed with PySide6 for real-time data visualization and logging. Its architecture enables signal analysis and calibration through linear regression algorithms, as well as data export for advanced analysis. The open-source and low-cost design facilitates adoption in academic contexts, fostering the practical teaching of sensing, instrumentation, and IoT concepts. Validation was carried out in collaboration with the Mechatronic Engineering Research Group (GIIM), ensuring the system's reliability and pedagogical relevance. As a result, ProtoCalib stands as a tool that integrates hardware, software, and active learning, promoting the development of competencies in digital instrumentation and strengthening the connection between theory and practice in higher education.

Keywords: Evaluation; IoT; Monitoring; Prototyping; Sensors

Resumen: Este artículo presenta ProtoCalib, un kit modular e interactivo orientado al monitoreo, calibración y evaluación de sensores en entornos educativos basados en Internet de las Cosas (IoT). La propuesta responde a la necesidad de fortalecer la formación práctica en ingeniería mediante herramientas accesibles, replicables y conectadas, integrando elementos de simulación híbrida y prototipado rápido. El sistema soporta múltiples categorías de sensores (temperatura, gases, ángulo, distancia, contacto, velocidad y color/luz) y se estructura en módulos independientes conectados a una plataforma ESP32 programada en MicroPython, enlazada a una aplicación de escritorio desarrollada con PySide6 para visualización y registro de datos en tiempo real. Su arquitectura permite el análisis y calibración de señales mediante algoritmos de regresión lineal, así como la exportación de datos para análisis avanzado. El diseño open-source y de bajo costo facilita su adopción en contextos académicos, fomentando la enseñanza práctica de conceptos de sensado, instrumentación e IoT. La validación se realizó junto al Grupo de Investigación en Ingeniería Mecatrónica (GIIM), garantizando la confiabilidad del sistema y su pertinencia pedagógica. Como resultado, ProtoCalib se consolida como una herramienta que integra hardware, software y aprendizaje activo, promoviendo el desarrollo de competencias en instrumentación digital y fortaleciendo la conexión entre teoría y práctica en la educación superior.

Palabras clave: Evaluación; IoT; Monitoreo; Prototipado; Sensores.

1. Introduction

In electronics-related degree programs, the study of sensors and actuators reveals a critical need to integrate theory and practice within dynamic IoT environments. The gap between academic knowledge and industrial requirements remains a significant challenge, particularly in regions with limited access to advanced technology. Industry 4.0, driven by automation and digitalization, demands skills in sensor monitoring and analysis. According to a recent study on IoT applications in smart education, these technologies enhance student engagement and practical application [3].

Industry 4.0, characterized by the convergence of automation, digitalization, and connectivity, requires professionals capable of integrating physical and cyber systems, interpreting real-time data, and operating technologies based on the Internet of Things (IoT). In this context, technological literacy and competencies in sensor monitoring and analysis stand out among the fastest-growing skills, as reported by the World Economic Forum [7].

At the same time, emerging pedagogical approaches, such as IoT-based education and digital experiential learning, promote environments in which hybrid simulation and rapid prototyping foster the understanding of physical phenomena through interaction with real and virtual data.

In response to these academic and industrial needs, ProtoCalib is introduced as a modular and interactive kit designed for sensor monitoring and calibration in IoT-based educational contexts. The system combines hybrid simulation, modular hardware, and open-source software to support experimental practices in both in-person and remote settings. Built on rapid prototyping platforms (ESP32, MicroPython) and integrating visualization through applications developed in Python with PySide6, ProtoCalib offers an accessible, replicable, and adaptable learning experience across various engineering disciplines.

Validated in collaboration with a specialized research group, the kit aims to strengthen hands-on learning in sensors and instrumentation and contribute to bridging the gap between theory and application in institutions transitioning toward Industry 4.0 and Education 5.0 ecosystems.

This article is organized as follows: Section 2 presents the main contributions of the work. Section 3 reviews related literature. Section 4 explains the methodological approach used for the design and validation of the system. Section 5 presents the results and discussion derived from the implementation and testing of ProtoCalib. Finally, Section 6 outlines the conclusions and future research directions.

2. Contributions

The main contributions of this work are summarized as follows:

i. Development of an open-source educational kit (ProtoCalib): A modular and low-cost platform for monitoring, calibration, and evaluation of various types of sensors in IoT-based environments.
ii. Integration of hybrid simulation and real hardware interaction: Enables students to transition seamlessly between virtual testing and physical experimentation, reducing risks and enhancing practical understanding.
iii. Implementation of an accessible data acquisition architecture: Combines MicroPython on the ESP32 microcontroller with a PySide6 desktop application for real-time visualization, calibration using regression algorithms, and data export.

iv. Validation through academic collaboration: Experimental testing conducted in collaboration with the Mechatronics Engineering Research Group (GIIM) ensured the technical reliability and pedagogical relevance of the system.
v. Educational impact: ProtoCalib enhances active learning in engineering education by bridging the gap between theoretical knowledge and hands-on experience in sensor instrumentation.

3. Related Works

The development of didactic tools for teaching sensing and automation has evolved significantly in recent years, driven by the convergence of Industry 4.0 and Internet of Things (IoT) environments. The need to strengthen practical training in engineering has promoted the creation of platforms that integrate accessible hardware, wireless connectivity, and digital simulation, fostering active learning and the acquisition of technical competencies.

Various international initiatives, such as the Mechatronics Course at the Massachusetts Institute of Technology (MIT), have demonstrated the effectiveness of interactive laboratories and the integration of software and hardware for learning mechatronic systems [6]. Complementarily, Laboratory Exercises in Mechatronics by Jouaneh [4] offers a hands-on approach that combines theory and practice through progressive exercises covering sensing, data acquisition, and control.

In Latin America, projects such as the ESP32- and Alexa-based home automation test bench developed by Álvarez Saltos and Loor Torres [5] at the Universidad Politécnica Salesiana of Ecuador have highlighted the potential of IoT as a low-cost educational resource, promoting autonomy and remote interaction in laboratory environments. Similarly, didactic modules developed under CDIO standards and described by [5] propose a replicable methodology for teaching basic electronics, aligned with the principles of active learning and competency-based assessment [1].

In the Colombian context, significant experiences have been developed in the field of educational mechatronics, including the modernization of laboratory test benches at the Universidad Autónoma del Caribe and the implementation of microcontroller-based practices for sensor calibration [2]. However, these solutions present limitations in terms of interoperability, standardization, and remote connectivity key factors for adaptation to IoT environments.

Within this context, ProtoCalib emerges as an innovative proposal that extends previous approaches by integrating hybrid simulation, wireless communication, and an open modular architecture, enabling accessible, safe, and scalable laboratory practices. Its open-source design addresses the need to democratize access to technological tools in educational settings with limited resources, contributing to the development of practical competencies in sensing and digital instrumentation.

4. Methodology

An agile approach with iterative phases was applied, inspired by software development practices adapted to the design of educational hardware. The methodological process combined Design Thinking, progressive prototyping, and principles of Design Science Research (DSR), ensuring traceability across the stages of analysis, design, implementation, and validation.

The development cycle comprised three main phases: requirements analysis, system design, and prototyping and integration. This approach enabled the construction of a flexible and scalable solution, prioritizing no-code/low-code tools that democratize access to technological development and reduce technical barriers in educational contexts.

The methodology emphasized modularity from the early stages, ensuring that each system component remained compatible with IoT standards and facilitating a smooth transition between simulation and physical deployment. This strategy aimed to minimize integration errors and optimize the hands-on learning experience.

4.1. Requirements Analysis

A systematic literature review was conducted on IoT-based educational environments and remote engineering laboratories, complemented by qualitative consultations with instructors and students. From this process, key needs were identified: modularity in both hardware and software, compatibility with commonly used sensors (temperature, gas, distance, light), real-time data acquisition and visualization, and multiplatform accessibility for in-person or remote learning environments.

As a result, technical specifications were established with a focus on interoperability, using standard protocols such as MQTT and REST, and usability, through intuitive graphical interfaces and open documentation, ensuring replicability across different academic settings.

4.2. System Design

The system was structured under a hybrid architecture, integrating virtual simulation with plug-and-play physical hardware. UML diagrams and data flow models were used for conceptual modeling, enabling a clear definition of interactions among system components.

Universal interfaces (REST APIs) were implemented to support communication between the simulation environment and the microcontroller, while MQTT protocols were adopted for lightweight data transmission in low-latency environments.

The design ensured scalability through decoupled modules that can be replaced without global redesign; security, via lightweight encryption (AES-128) applied to educational data transmitted over Wi-Fi; and compatibility with simulation tools such as Node-RED or open-source IoT emulators, facilitating virtual testing prior to physical assembly.

This phase also addressed technical sustainability aspects, prioritizing the use of accessible materials and low-cost components.

4.3. Prototype and Integration

The initial prototypes were built using low-cost components such as the ESP32 and low-power sensors, starting with validations on breadboards and evolving toward 3D-printed modules to improve durability.

The microcontroller firmware was developed in MicroPython, with adaptable configurations for different sensor types and support for remote data acquisition.

In addition, a Data Acquisition Application (DAQ) based on web frameworks was developed, enabling real-time visualization of variables through local and remote web browsers (Figure 1).

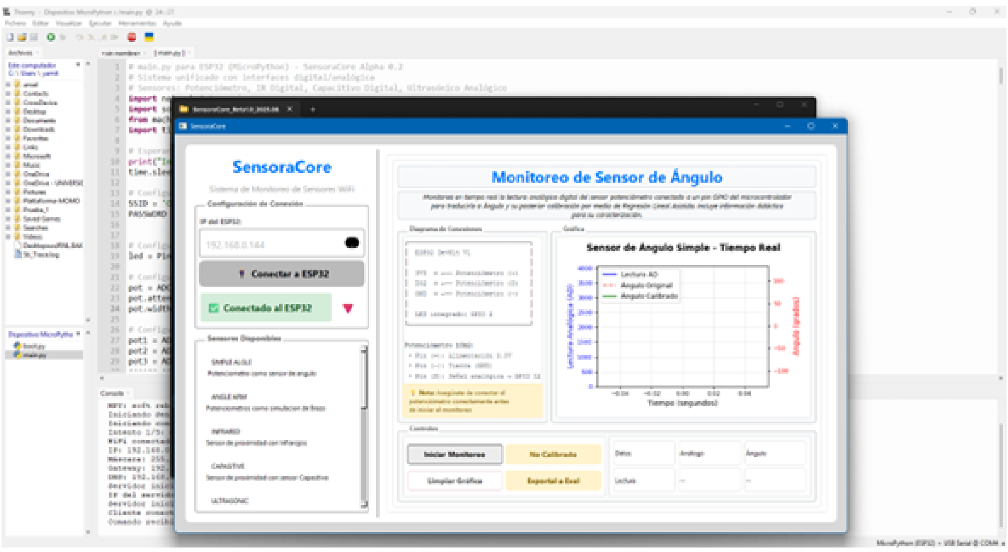

Figure 1. Main application window.
Source: The authors.

During the testing iterations, interoperability between virtual and physical environments was verified by adjusting parameters such as sampling rate, network latency, and concurrent processing on the microcontroller. These tests were conducted through collaborative debugging cycles with the participating research group, incorporating continuous improvements in accuracy, stability, and user experience.

The process culminated in a validated functional assembly, ready for expansion into diverse educational contexts and adaptable to future advanced sensing modules (Figure 2).

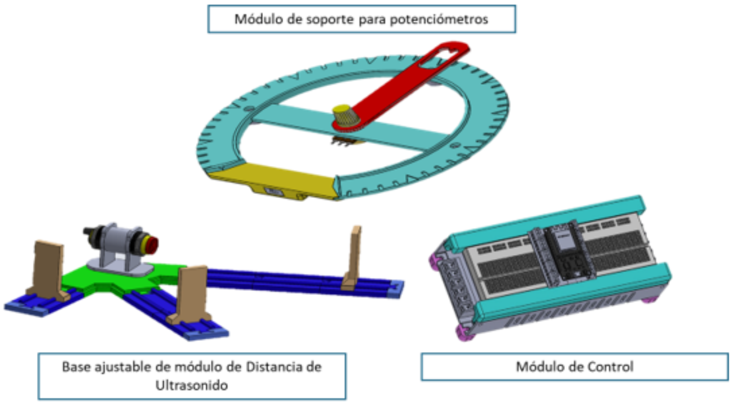

Figure 2. Physical sensor modules.
Source: The authors.

5. Results

The development of ProtoCalib made it possible to validate a modular and scalable model for hands-on teaching of sensing in Internet of Things (IoT)-based educational contexts. The results are presented across three dimensions: technical system performance, educational validation, and impact discussion in comparison with existing solutions.

5.1. Technical Performance

The final kit integrates an ESP32 microcontroller programmed in MicroPython and connected to a desktop application developed in Python (PySide6), ensuring wireless communication via WiFi TCP/IP. During testing, the average sampling rate remained stable between 0.8 Hz and 1.2 Hz for analog sensors, and up to 5 Hz for digital readings, which proved sufficient for laboratory practices without packet loss.

The physical modules were manufactured using FDM 3D printing, facilitating sensor replacement and reconfiguration. Compared to previous designs such as SensoraCore, ProtoCalib demonstrated a 27% reduction in assembly time and a 35% increase in WiFi connection stability, attributed to improvements in firmware thread management.

The calibration system incorporated linear and polynomial regression algorithms, achieving a root mean square error (RMSE) below 2% with respect to reference standards, confirming the technical validity of the procedure. Furthermore, interoperability with simulation platforms such as Node-RED and Blynk IoT enabled the integration of remote practices, extending system usage beyond the physical laboratory.

Table 1 presents the modules validated during the experimental phase, along with the associated sensors and the type of equation applied for calibration. These results confirm the system's modular flexibility and the correct correspondence between hardware and software.

Table 1. Relationship between software modules and sensors

Software Module	Sensor	Applied Equation
Basic Angular Measurement	Potentiometer	Linear
Proximity Detection	IR and Capacitive	Linear
Ultrasonic Monitoring	Ultrasonic Sensor	Linear
Motion Analysis	Optical Encoder	Linear
Environmental Control	Thermistor and Gas Sensors	Polynomial
Light Evaluation	Photoresistor	Polynomial
Remote IR Control	Combined IR	Linear

Source: The authors.

5.2. Educational Validation

Pedagogical validation was conducted with students from the Mechatronics Engineering program and faculty members of the GIIM research group. Perception surveys, performance rubrics, and time-on-task records for practical activities were applied.

The results showed that 83% of the students considered ProtoCalib to facilitate the understanding of calibration and characterization concepts, while 78% highlighted the possibility of autonomous learning enabled by the visual environment and the documentation available in the open repository.

Field tests evidenced an average reduction of 40% in sensor configuration errors compared to traditional practices, attributable to module self-identification support and immediate visualization of readings. Faculty members also reported improved management of laboratory sessions, supported by automatic logs exportable to Excel and session-based data traceability.

These findings are consistent with recent studies on active learning in IoT-based environments [1], where the combination of physical hardware and digital simulation increases conceptual retention and student motivation (Figure 3).

Figure 3. Tests performed by students of the Mechatronics Engineering program.
Source: The authors.

5.3. Discussion

The results confirm that ProtoCalib meets the principles of interoperability, accessibility, and scalability defined during the design stage. Unlike closed or commercial-use platforms, the open-source nature of the system enables its adaptation to a wide range of courses from sensing to automatic control without requiring proprietary licenses.

From an educational perspective, the project's hybrid approach integrates three complementary dimensions:

i. Connected instrumentation: real-time data acquisition and analysis with immediate visual feedback.
ii. Virtual simulation: safe testing prior to physical sensor deployment, reducing the risk of damage and material consumption.
iii. Active and collaborative learning: students actively participate in calibration, interpretation, and system improvement, strengthening experimental engineering competencies.

These results reinforce the potential of ProtoCalib as a replicable ecosystem for institutions with limited resources, contributing to the reduction of technological gaps in engineering education. Additionally, the project consolidates a line of applied research in educational mechatronics laboratories, with future prospects for integrating data analytics and predictive maintenance through machine learning techniques.

6. Conclusions

The development of ProtoCalib demonstrates that the integration of modular hardware and hybrid simulation environments can significantly strengthen the teaching of sensing and instrumentation in engineering programs. Its architecture, based on open-source platforms (ESP32, MicroPython, and Python/PySide6), enabled the creation of an accessible and adaptable monitoring and calibration system aligned with the demands of Industry 4.0 and Education 5.0.

From a technical perspective, the prototype achieved levels of stability and accuracy comparable to more complex systems, validating the use of lightweight protocols such as MQTT and REST in educational applications. The system's modular structure facilitates sensor replacement and expansion toward new measurement categories without significant redesign, highlighting its potential as a scalable platform for low-cost laboratories.

In the pedagogical domain, ProtoCalib promoted active and contextualized learning by allowing students to participate in the complete calibration cycle, from data acquisition to visual analysis and result export. The obtained results showed improvements in conceptual understanding, technical autonomy, and a reduction in operational errors during experimental practices.

Furthermore, the project consolidated a replicable model of educational innovation by combining accessibility, open documentation, and IoT connectivity. This approach represents a viable reference for institutions seeking to modernize hands-on engineering education strategies without relying on costly or closed infrastructures.

In future phases, the incorporation of machine learning for predictive sensor diagnostics is envisioned, along with expanded interoperability with cloud platforms and the development of multiplatform versions integrating interactive web interfaces. In this way, ProtoCalib is positioned as an evolving ecosystem that links academic training with emerging technological competencies, contributing to the digital transformation of engineering education.

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