

An Offline, Computer-Less Infrastructure for Scalable Physics Laboratory Learning

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Abstract

Hands-on experimentation is central to physics education, yet laboratory access remains inequitable. Many schools in rural India, Africa, and other under-resourced regions lack affordable lab infrastructure, often relying on costly proprietary ecosystems such as Vernier or PASCO that require dedicated interfaces, sensors, and external computers. We present a low-cost, fully embedded physics lab device built around an ESP32 microcontroller that integrates multiple sensors, real-time visualization, and structured guided lessons without requiring internet connectivity or external computers. The system supports modular sensors, interactive graphing modes, and workbook-integrated activities. Through a Newton's Second Law ($F = ma$) lesson using an onboard IMU, we demonstrate how embodied interaction, real-time data visualization, and written corroboration can be tightly coupled to strengthen conceptual and quantitative reasoning. This work-in-progress describes system architecture, interface design, pedagogical integration, and future expansion plans.

CCS Concepts

• **Applied computing** → **Education**; *Interactive learning environments*; • **Human-centered computing** → Ubiquitous and mobile computing systems and tools.

Keywords

Low-cost hardware, Embedded systems, Physics education, STEM equity, Offline learning technologies

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1 Introduction

Physics laboratories are essential for deep conceptual understanding: students learn more effectively when they can manipulate physical systems, observe measurable outcomes, and connect those observations to mathematical models. Decades of research in science and engineering education emphasizes the value of active, hands-on engagement for improving conceptual learning outcomes

relative to purely passive instruction [1, 7]. Laboratory work, in particular, supports inquiry, measurement, and model-based reasoning, and remains a foundational component of science education [2]. These priorities are reflected in major curriculum frameworks that emphasize scientific practices—including planning investigations, analyzing data, and using mathematics/computation—as core elements of K–12 science learning [5, 6].

Despite its importance, lab access remains inequitable. In many rural schools across India, Africa, and other low-resource regions, laboratory instruction is limited or absent due to cost and infrastructure constraints. Commercial systems such as Vernier and PASCO provide high-quality sensors and software, but typically require proprietary sensor ecosystems, interface modules, and external computers—placing them financially and logistically out of reach for under-resourced classrooms. As a result, many students experience physics as theoretical rather than empirical.

Meanwhile, recent educational work has highlighted the potential of commodity sensing to make measurement-driven activities more accessible. Smartphone-based experiments demonstrate that embedded sensors (e.g., accelerometers and gyroscopes) can support meaningful physics inquiry and allow students to connect real motion to real data [3, 4]. However, smartphones introduce practical limitations in low-resource settings: inconsistent availability, battery and device management, classroom fragility, and dependence on personal ownership.

To address these constraints, we propose a self-contained, low-cost embedded physics lab platform. The device integrates sensing, computation, visualization, and guided instruction into a single portable unit. It operates fully offline and requires no external computer, internet connection, or proprietary ecosystem. Our goal is to provide scalable, accessible laboratory experiences for classrooms with limited infrastructure while preserving the core pedagogical cycle of experimentation: perform an action, observe measured data, and reason quantitatively about the result.

2 System Overview

Figure 1 presents the system architecture. Sensor inputs (internal and external) feed into an ESP32 microcontroller. Analog signals pass through an ADC when required, while digital sensors communicate directly via I2C or SPI. The ESP32 processes data and renders real-time visualizations on an embedded display.

For demonstration, we implemented four sensors:

- Light Dependent Resistor (LDR) – ambient light measurement
- IMU – acceleration and orientation
- Temperature sensor – environmental sensing
- Force Sensitive Resistor (FSR) – applied force measurement



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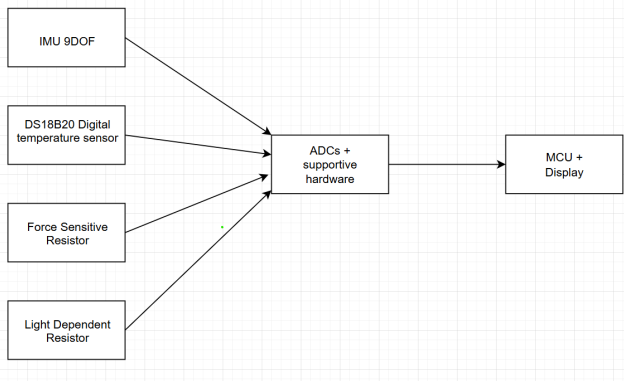


Figure 1: System overview: sensor inputs flow through processing on the ESP32 and are visualized directly on the embedded display.

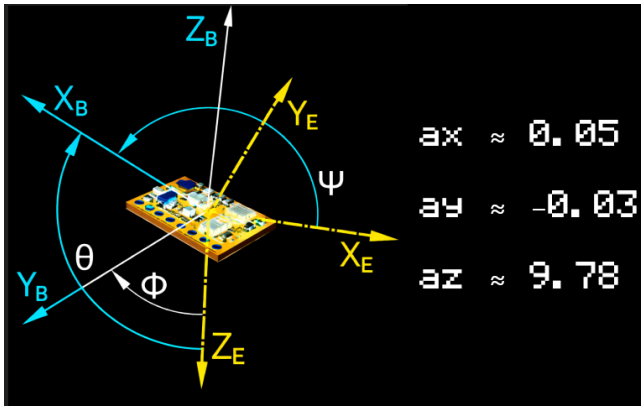


Figure 2: IMU familiarization screen. Students manipulate the device and observe real-time changes across X, Y, and Z axes.

Some sensors (IMU, FSR) are embedded directly into the device for immediate interaction. Others (e.g., temperature, ultrasonic in future versions) connect modularly via JST ports. This architecture enables extensibility while maintaining low cost.

Lessons, diagrams, and prompts are embedded directly into firmware, allowing the device to function independently as both lab instrument and instructional interface.

3 Sensor Familiarization

Before structured labs, students are introduced to individual sensors. Figure 2 shows the IMU familiarization screen.

The IMU measures acceleration across three orthogonal axes (X, Y, Z). Students are prompted to move and rotate the device while observing live numerical changes and graph updates. This embodied interaction grounds abstract vector quantities in tangible motion.

This stage builds sensor literacy: students learn what the sensor measures and how physical motion maps to numerical data.

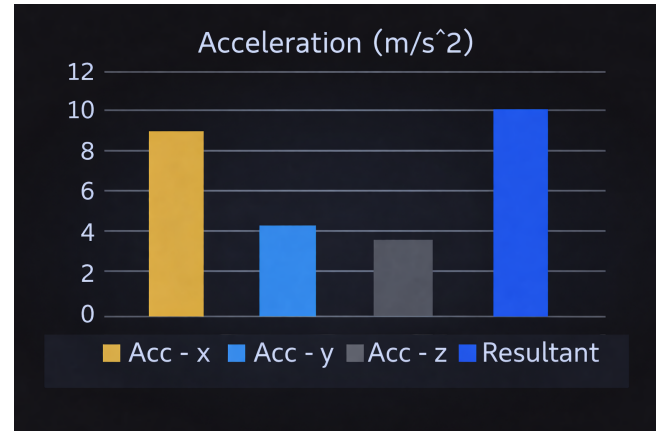


Figure 3: Bar graph mode enables comparison of peak values across multiple experimental runs.

4 Example Lesson: Newton's Second Law

To support understanding of Newton's Second Law ($F = ma$), the device implements a guided IMU-based activity.

Students first learn what the IMU measures: acceleration and orientation. The workbook corroborates this information, containing fill-in-the-blank sections tied to measured values.

Students then perform controlled actions (e.g., gentle and forceful pushes). The device computes acceleration and calculates force using measured mass. A live graph displays acceleration over time, with peak values highlighted.

Each activity follows a structured cycle:

- (1) Perform a physical action.
- (2) Observe acceleration and computed force on the display.
- (3) Record peak values in the notebook.
- (4) Compare trials and reason proportionally.

By tightly coupling embodied interaction, real-time visualization, and written corroboration, the proportional relationship in $F = ma$ becomes empirically visible. Students measure rather than merely calculate.

5 Graphing and Interaction Modes

When "Area" mode is selected, the information panel switches from live sensor readings to cursor-selected values (Figure 4). This enables examination of specific data points and supports quantitative reasoning about integrals and peaks.

6 Implementation

To accelerate iteration without repeatedly flashing firmware, we maintain a Python-based renderer that reproduces the embedded UI layout and styling, enabling rapid testing of icon placement, typography, and graph aesthetics before deployment on the device.

Sensor values are sampled at fixed intervals and mapped to screen coordinates using:

$$x = \frac{t}{T_{max}} \cdot W \quad y = H - \left(\frac{v - v_{min}}{v_{max} - v_{min}} \cdot H \right)$$

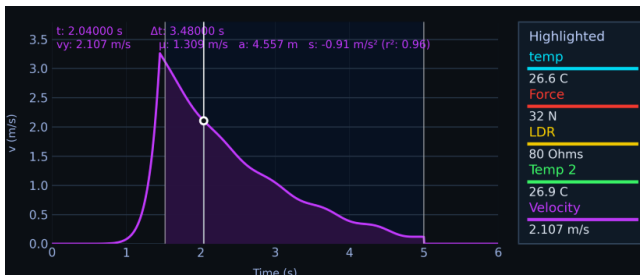


Figure 4: Area mode showing cursor-selected graph values instead of live sensor data. Prototype rendered image only. Not implemented on device.

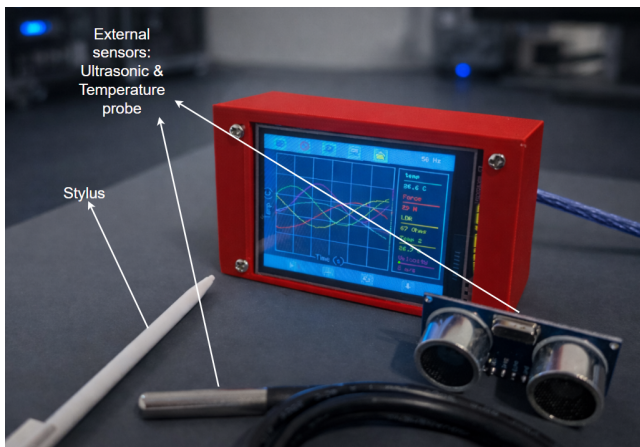


Figure 5: Current prototype display with integrated and modular sensors. The device features an embedded touchscreen display supporting real-time graphing and interaction via stylus. Built-in sensors (e.g., IMU, FSR) enable immediate experimentation, while external modules such as ultrasonic distance and temperature probes connect via JST ports.

where W and H define graph dimensions. This ensures consistent scaling across trials. All computation and rendering occur locally.

7 Future Work

Future iterations will include SD card-based file saving. When inserted, students will be able to store experimental runs directly on-device, enabling persistent storage without external computers. In addition, it will feature a much wider scope of sensors to cover a broader range of Physics and STEM concepts.

Planned classroom pilots in India and other under-resourced settings will evaluate usability, learning gains, and long-term durability.

8 Conclusion

We present an embedded physics lab platform designed for scalable, offline STEM education. By integrating modular sensors, real-time visualization, and workbook-driven structured activities into a single device, the system reduces barriers to laboratory access

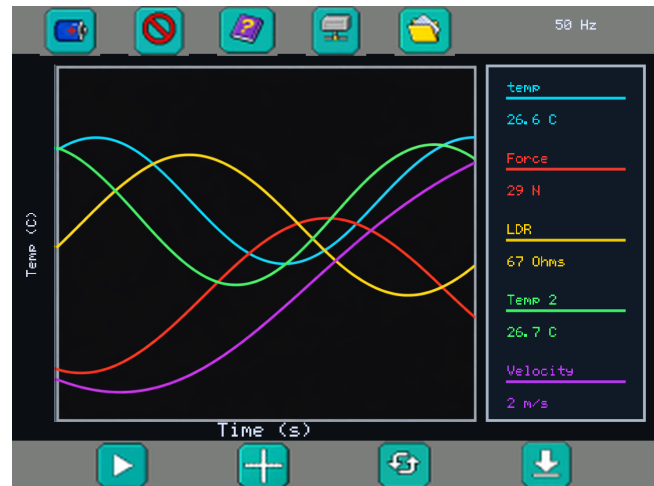


Figure 6: Main menu / graphing interface (rendered via a Python preview script that mirrors the on-device TFT layout). The top row provides system-level controls: battery status, exit module, help, sensor settings, and open file. The bottom row provides experiment controls: run/stop, add run, reset, and save data.

in under-resourced settings. Through embodied interaction and quantitative reinforcement, it transforms abstract physics principles into measurable phenomena without reliance on proprietary ecosystems or external computing infrastructure. A pilot deployment is planned in collaboration with Atal Tinkering Labs in India to evaluate classroom integration, usability, and learning outcomes in resource-constrained environments.

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