Development of a hands-on experiment for one-dimensional straight motion based on IoT

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Article History
Received: 2 February 2026
Revised: 23 May 2026
Accepted: 16 July 2026

Keywords
Hands on experiment
Internet of Things
Investigative
Kinematics

Abstract
This study aims to develop and evaluate an Internet of Things (IoT)-based hands-on experimental apparatus for one-dimensional linear motion in terms of technical performance, usability, and its initial potential to support students' investigative activities. The study employed a development model comprising conceptual design, design realization, prototype fabrication, and prototype evaluation stages. The prototype was developed by integrating a NodeMCU ESP8266, an HC-SR04 ultrasonic sensor, the Blynk application, an electric pulley system, and 3D-printed mechanical components. Technical evaluation was conducted by comparing the position-versus-time data from the prototype with video analysis results obtained using Tracker software. A limited trial was conducted with 12 Physics Education students using a one-group pretest–posttest design integrated with Investigative Science Learning Environment (ISLE) worksheets. Technical evaluation results indicated that the prototype consistently recorded object motion patterns, achieving an R^2 value of 0.9992, whereas Tracker obtained an R^2 value of 0.971. The limited trial demonstrated moderate improvements in science process skills and graphical representation, with normalized gain (N-gain) values of 0.51 and 0.50, respectively. Paired-samples t-test results showed statistically significant differences between pretest and posttest scores for both aspects. Student responses toward the apparatus fell into the "very good" category. These findings indicate that the prototype has the potential to support investigation-based physics laboratory activities, assist students in obtaining real-time experimental data, and strengthen the analysis of relationships among position, time, and graphical representations. Furthermore, the use of affordable electronic components and 3D printing highlights the potential of the apparatus as a flexible and relatively easily replicable laboratory alternative.

Mafudi, I., Kuswanto, H., Rahmat, A, D., & Fatmawati, I. (2026). Development of a hands-on experiment for one-dimensional straight motion based on IoT. *Momentum: Physics Education Journal*, *10*(1), 187-197. https://doi.org/10.21067/mpej.v10i1.13865

1. Introduction

Physics laboratory instruction has shifted from confirmatory experiments toward a more investigation-based approach (Holmes & Lewandowski, 2020; Kontro et al., 2018; Kozminski et al., 2014; Narayanan et al., 2023). The investigative approach enables students to actively engage in exploration, data collection, and experimental data analysis, which fosters enhanced conceptual understanding of physics (Chen et al., 2012; Rutberg et al., 2023). To support this transformation in physics laboratory learning, experimental apparatuses capable of providing authentic, accurate, and real-time data through modern technology are required.

Various linear motion experimental apparatuses providing authentic and real-time data using different technologies have been developed and commercially distributed. The utilization of Arduino Uno technology in the prototype of the P-PAM (Physics Practicum Apparatus based on Microcontroller) showed promising results; however, evaluation indicated the need to replace the Arduino microcontroller with an ESP module and establish a dedicated track to ensure straight-line motion (Syamsiah et al., 2024). Another study developed a linear motion kinematics apparatus utilizing microcontrollers and LDR sensors, yet it lacked IoT technology integration (Istiantara et al., 2019). Similar linear motion equipment is available on the market, such as the Dynamics Cart and

doi: 10.21067/mpej.v10i1.13865
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ISSN: 2548-9135

Track System with Go Direct® Sensor Carts or the simpler Go! Motion; however, the commercial prices for both systems remain prohibitively high. High-cost infrastructure often poses a major constraint for higher education institutions (Fajrin & Lukman Hakim, 2022). An ideal solution that balances affordability with high performance lies in utilizing Internet of Things (IoT) technology.

The application of IoT technology in physics experiments offers significant potential (Irwandi et al., 2020; Organtini & Tufino, 2022). This technology enables real-time data measurement, which can subsequently be accessed and analyzed via cloud-based applications (Ansari et al., 2022). By employing IoT-based sensors and devices, experimental data can be automatically collected and immediately rendered in intuitive formats, such as graphs or tables, thereby supporting visual data representation (Asrizal et al., 2024; Ou et al., 2025). Technology-enhanced laboratories reduce the time spent on data collection and graphing (Brungardt & Zollman, 1995; Kelly & Crawford, 1996). Integrating technology into physics laboratory education enriches student learning experiences, fosters science process skills, and facilitates a deeper understanding of physics concepts (Chen et al., 2012; Husnaini & Chen, 2019; Lahme et al., 2023). Technology not only simplifies experimental data acquisition but also aids students in comprehending physics concepts through direct observation of the tested object's motion patterns. Based on these requirements, this study aims to develop and evaluate an Internet of Things-based hands-on experimental apparatus for one-dimensional linear motion in terms of technical performance, usability, and its initial potential to support students' investigative activities.

2. Method

This study adopted a structured engineering design methodology adapted from (Dieter & Schmidt, 2021). The process commenced with the conceptual design phase, wherein user requirements were identified and the initial system concept was formulated by creating circuit schematics, block diagrams, and flowcharts to illustrate the system workflow. In the design realization phase, 3D modeling of the apparatus was conducted including experimental objects such as the cart and track alongside microcontroller code development to ensure alignment between the physical design and the initial concept. The prototype fabrication phase involved assembling the apparatus according to the design to evaluate its functionality. The prototype evaluation phase encompassed technical evaluation and limited user testing.

The technical evaluation was performed by comparing position-versus-time data generated by the prototype with video analysis data obtained using Tracker software. The limited user trial was conducted to assess the usability of the apparatus and its initial potential to support students' investigative activities. The limited trial employed a pre-experimental one-group pretest–posttest design involving 12 students. Science process skills and graphical representation abilities were measured before and after students conducted experiments using the prototype integrated with Investigative Science Learning Environment (ISLE) worksheets (Etkina & Planinsic, 2024). Data were analyzed using normalized gain (N-gain) and paired-samples t-tests after satisfying normality assumptions based on the Shapiro–Wilk test. Effect size was determined using Cohen's d. Prototype usability was measured via a questionnaire covering aspects of usefulness, ease of use, ease of learning, and satisfaction. The overall research workflow is illustrated in Figure 1.

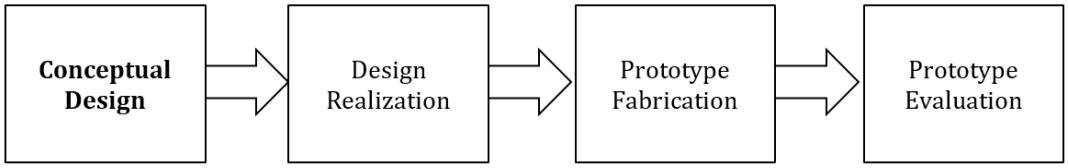


Figure 1. Research Flow of The Study

3. Results and Discussion

3.1. Conceptual Design

The conceptual design phase was conducted by translating the functional requirements of the apparatus into the design of a measurement system, a drive system, and an Internet of Things-based data communication architecture. These three designs were developed to enable the apparatus to

facilitate both uniform linear motion (ULM) and uniformly accelerated linear motion (UALM) experiments, while simultaneously measuring and displaying position data of the object in real time.

The measurement system utilized a NodeMCU ESP8266 microcontroller board as the primary controller and an HC-SR04 ultrasonic sensor to measure object position. The NodeMCU processed the measurement data and transmitted them wirelessly to the Blynk application. A 5 V battery provided power for the NodeMCU and sensor, enabling standalone system operation. The component configuration of the measurement system is shown in Figure 2.

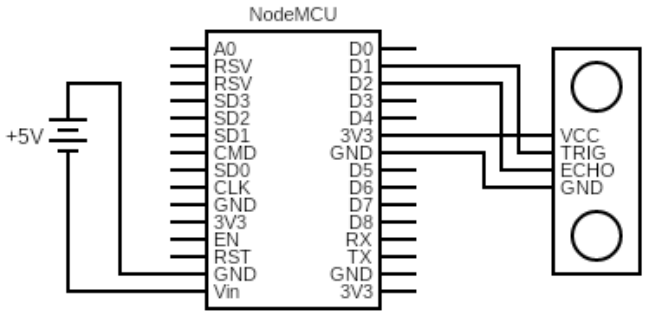


Figure 2. Schematic diagram of the measurement system

In UALM experiments, velocity variations are obtained through the gravitational force component along an inclined track. Conversely, ULM experiments require object movement along a horizontal track at a relatively constant velocity. This condition necessitates an external drive system capable of supplying a more stable and controlled pulling force, as manual actuation tends to introduce force variations that compromise velocity consistency. To address this requirement, an electric motor connected to a 7 V power supply and a pulley was employed to pull the object along the track. A push-button switch was used to activate and deactivate the motor according to the experimental stages. The drive system circuit supporting ULM experiments is shown in Figure 3.

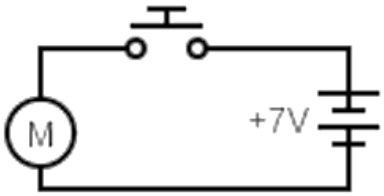


Figure 3. Schematic diagram of the electric pulley system

The Internet of Things-based experimental apparatus was designed to integrate real-time data measurement, processing, transmission, and rendering. The HC-SR04 sensor at the perception layer measured the object position, whereas the NodeMCU ESP8266 at the network layer processed and transmitted data wirelessly to Blynk Cloud as the middleware layer. The data were subsequently displayed at the application layer via the Blynk application, accessible on a computer or smartphone. The system architecture and data flow are presented in Figure 4.

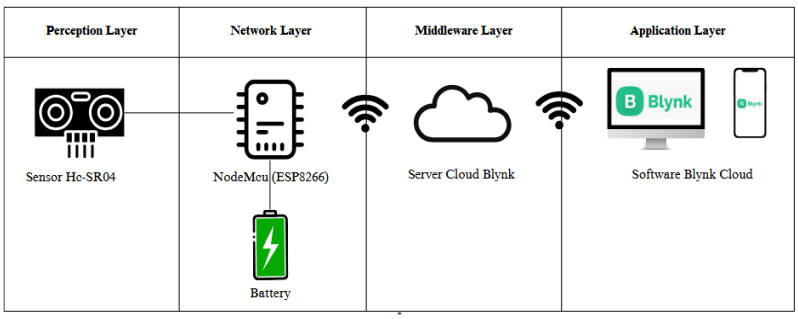


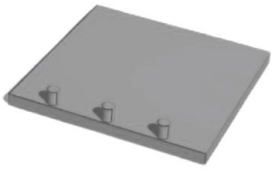
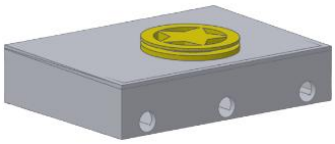
Figure 4. Block diagram of IoT architecture and data transmission

Data acquisition is activated via the start button in the Blynk application. The sensor records the object position every 200 ms, after which the NodeMCU periodically transmits data to Blynk Cloud until the user halts the process using the stop button. This mechanism enables automated and controlled experimental data acquisition and monitoring.

3.2. Design Realization

The design realization phase was conducted by developing three-dimensional models of the one-dimensional linear motion experimental apparatus components using the open-access Tinkercad platform (https://www.tinkercad.com/). The designed components included a moving cart, a track, a sensor reflector, and an electric pulley housing. Each model was subsequently exported in Standard Tessellation Language (STL) format and converted into G-code using Creality slicing software to generate instructions for the printing process. The G-code files were then used to fabricate the components with a 3D printer according to the geometry and dimensions specified in the design. The component types, three-dimensional models, and functions of each component are presented in Table 1.

Table 1. 3D Component Design

Component	Design	Fuction
Object		This component functions as both the moving object and a platform for mounting the ultrasonic sensor, NodeMCU, and battery, allowing the tool to move while simultaneously measuring the distance.
Track		The track serves as the path for the object to move, ensuring that it follows the predetermined route.
Reflector Sensor		The reflector sensors bounce the signal sent by the sensor, allowing it to measure the distance of the object as it moves.
Electric Pulley		The electric pulley system, driven by an electric motor, is used to pull the object during the uniform straight motion experiment.

In addition to mechanical design, this phase included microcontroller code development to regulate data acquisition and transmission. The HC-SR04 sensor measured the object position every 200 ms, after which the NodeMCU ESP8266 converted the data into meters and transmitted them to the Blynk application via virtual pin V1. The measurement process was activated and deactivated via a virtual button assigned to pin V0. This mechanism enabled automated, real-time measurement and monitoring of the object position.

3.3. Prototype Fabrication

The prototype fabrication phase was conducted by integrating mechanical, electronic, and IoT system components based on the results of the conceptual design and design realization phases. The assembled components included a track, a moving cart, a reflector, an electric pulley system, an HC-

SR04 ultrasonic sensor, a NodeMCU ESP8266, a battery pack, and a Blynk application user interface. This integration yielded a one-dimensional linear motion experimental apparatus capable of measuring object position and displaying measurement data in real time. The physical configuration of the prototype and its component arrangement are shown in Figure 5.

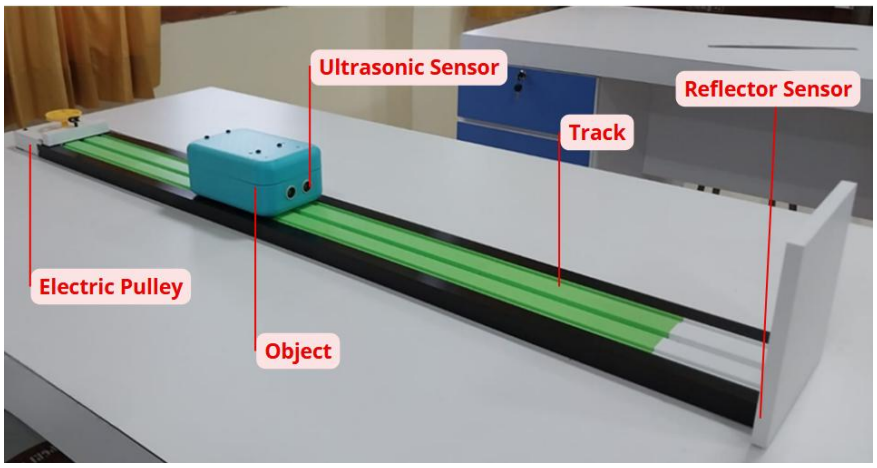


Figure 5. Assembled prototype of the linear motion experimental apparatus

Prototype fabrication also demonstrated the potential of the apparatus as a relatively low-cost laboratory device. This potential stems from an in-house manufacturing strategy utilizing 3D printing and the selection of readily accessible electronic components. The majority of mechanical components such as the track, moving cart, sensor mounts, reflector, pulley housing, and other supporting elements were fabricated using a 3D printer. The track was designed in a modular, interlocking structure with each section measuring 15 cm in length, thereby allowing track length customization according to experimental requirements. PLA+ filament was utilized for this prototype as it allowed component geometry, thickness, and print quality to be tailored to design requirements. The use of this material clearly distinguishes the prototype from commercial tracks, which are typically constructed from precision aluminum rails.

Open-source hardware-based 3D printing enables the development of scientific instruments that are lower in cost, easily customizable, and widely replicable for both research and educational equipment development (Zhang et al., 2013, 2016). Beyond mechanical aspects, the low-cost nature of the prototype is reinforced by the employment of affordable electronic components namely the NodeMCU ESP8266 and HC-SR04 ultrasonic sensor to establish more accessible and flexible physics laboratory activities (Bouquet et al., 2017; Çoban & Çoban, 2020). Consequently, the low-cost aspect of this prototype derives not only from component prices but also from the capability of the apparatus to be fabricated in-house, customized as needed, reprinted, and replicated for introductory physics laboratory activities.

3.4. Prototype Evaluation

3.4.1. Calibration Test

A technical calibration test was conducted to evaluate the accuracy and reliability of the developed prototype apparatus in measuring object movement in one-dimensional motion experiments. The test was performed by comparing the measurement results obtained from the prototype apparatus with video tracking data obtained using Tracker software. This evaluation process aimed to ensure that the developed apparatus yields consistent and precise data and remains reliable across various measurement conditions. Figure 6 presents a graph illustrating the measurement data obtained using the IoT-based prototype apparatus; the relationship between object position s and time t fits a quadratic model remarkably well. The resulting Equation (1) is expressed as follows:

$$y = 0.0746x^2 + 0.1318x - 0.0092 \quad (1)$$

An R^2 value of 0.9992 indicates an exceptionally high degree of fit between the quadratic model and the acquired measurement data. This indicates that the prototype apparatus consistently measures object position and is reliable.

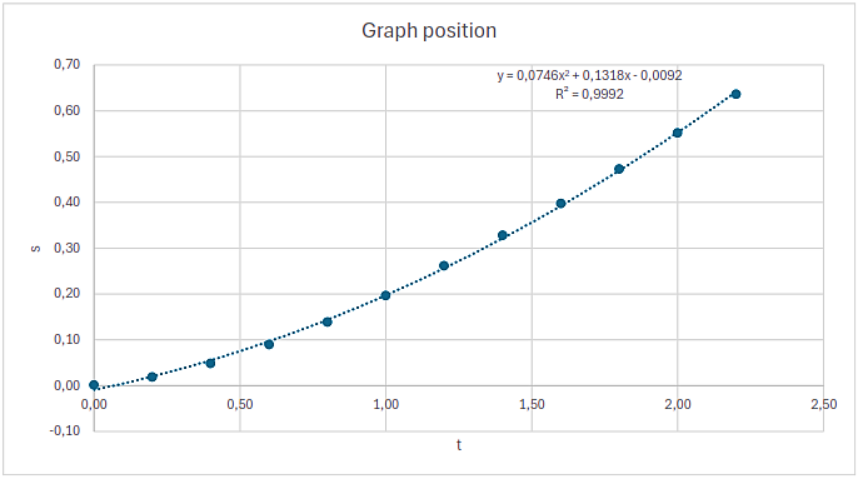


Figure 6. Position versus time graph and best-fit curve for the prototype data

In Figure 7, the test results using Tracker software demonstrate an excellent relationship between object position and time. The resulting Equation (2) is:

$$y = (0.06376\ )x^2 + (0.09347)x + (0.09002) \qquad (2)$$

An R^2 value of 0.971 indicates that the parabolic model effectively describes the measurement data, despite exhibiting a slightly lower R^2 value compared to the prototype apparatus. Nevertheless, these results confirm that Tracker provides reasonably accurate measurement results.

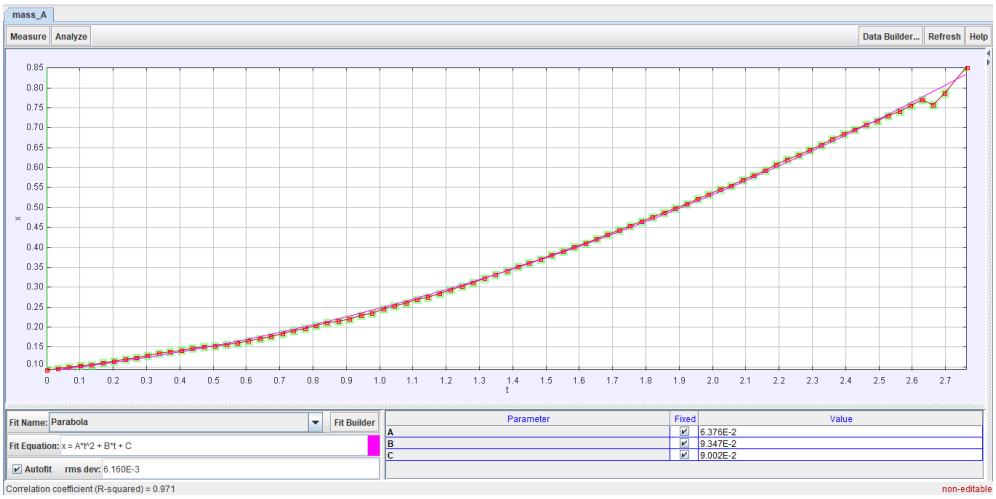


Figure 7. Position-versus-time graph and best-fit curve from Tracker analysis

Test results showed that position-versus-time data obtained from both the prototype and Tracker software formed motion patterns aligned with the characteristics of one-dimensional linear motion. The R^2 values of 0.9992 for the prototype data and 0.971 for the Tracker data demonstrate good agreement with the quadratic model. The slight difference in these values indicates that the prototype is capable of recording object motion patterns consistently and in alignment with analysis using Tracker. Thus, the developed prototype apparatus can serve as a supporting device for one-dimensional linear motion experimental activities in introductory physics laboratory courses. However, a more direct assessment of accuracy requires a more comprehensive measurement error analysis in future studies.

3.4.2. Limited Trial

The limited trial demonstrated positive initial results regarding the use of the IoT-based linear motion experimental apparatus integrated with ISLE worksheets. These results were analyzed based on the comparison of pretest and posttest scores for science process skills (SPS) and graphical representation (GR) abilities. Prior to conducting the paired-samples t-test, the data were tested for normality using the Shapiro–Wilk test, with the criterion for normally distributed data set at $p > 0.05$. Shapiro–Wilk test results indicated that both SPS and GR data in the limited trial satisfied the normality assumption. Furthermore, normalized gain (N-gain) calculations yielded values of 0.51 for SPS and 0.50 for GR, both falling into the "moderate" category (Hake, 1998). The normality test and N-gain results are presented in Table 2.

Table 2. Pretest and post-test results for SPS and GR in the limited trial

Test	Data	N	Shapiro-wilk	P value of Shapiro-wilk	N-gain
SPS	Pretest	12	0.894	0.134	0.51
	Posttest		0.942	0.522	
	Posttest – Pretest		0.897	0.146	
GR	Pretest		0.900	0.158	0.50
	Posttest		0.896	0.141	
	Posttest – Pretest		0.920	0.287	

Paired-samples t-test results indicated statistically significant differences between pretest and posttest scores for both SPS and GR ($p < 0.001$). Cohen's d values of 3.106 for SPS and 2.684 for GR indicated an extremely large effect size (Tellez et al., 2015). These findings provide an initial indication that integrating the IoT-based linear motion experimental apparatus with ISLE worksheets has the potential to foster students' science process skills and graphical representation abilities. The paired-samples t-test results are presented in Table 3.

Table 3. Paired-samples *t*-test results for SPS and GR in the limited trial

Test	Measure 1	Measure 2	t	df	p	Cohen's d
KPS	Posttest	Pretest	-10.761	11	< 0.001	3.106
RG	Posttest	Pretest	-9.298	11	< 0.001	2.684

In the limited trial, student responses toward the microcontroller-based linear motion experimental apparatus were also evaluated. Responses were collected using a questionnaire assessing Usefulness, Ease of Use, Ease of Learning, and Satisfaction following the learning activity. Student evaluation results for the experimental apparatus are presented in Table 4.

Table 4. Student responses toward the experimental apparatus in the limited trial

Aspect	Mean	Category
Usefulness	3.44	Very good
Ease to Use	3.45	Very good
Ease of Learning	3.48	Very good
Satisfaction	3.52	Very good

Overall, student responses indicated that the linear motion experimental apparatus received very good ratings. All evaluated aspects fell into the "very good" category, with mean scores ranging from 3.44 to 3.52 (Widoyoko, 2016). These findings reflect that the experimental apparatus not only functions effectively to support learning but is also easy to use and delivers user satisfaction. The apparatus successfully met student expectations in terms of practical functionality and ease of use. Nevertheless, these results should be interpreted with caution, as the trial was conducted with a single group of limited participants without a control group.

The development of this prototype apparatus carries significant implications for enhancing the effectiveness and efficiency of physics learning, particularly in one-dimensional linear motion experiments. The utilization of internet-based wireless technology enables real-time data transmission, eliminating dependence on cables and enhancing mobility and flexibility during experiments (Minh et al., 2023). The deployment of an ultrasonic sensor in this prototype not only improves the accuracy of object position measurements across time increments but also holds

significant implications for the effectiveness of the apparatus in one-dimensional linear motion experiments. Unlike infrared (IR) sensors or photodiodes, which can only be positioned at discrete points along a track (Listiaji et al., 2020; Syamsiah et al., 2024; Uzal, 2022), the ultrasonic sensor enables continuous position measurement along the entire track length, yielding more dynamic and accurate data (Sze et al., 2022). This capability facilitates real-time tracking of object positions at various time points without spatial constraints, providing a more precise representation of object motion patterns. The implementation of Blynk for data handling and visualization allows convenient access and monitoring of experimental results directly through a mobile-based application (Ramesh et al., 2022).

Technical calibration results demonstrated that the prototype consistently recorded object motion patterns in alignment with the characteristics of one-dimensional linear motion. This calibration is critical because sensor-based laboratory apparatuses are required not only to display data in real time but also to produce reliable data suitable for physical concept analysis. In this study, calibration was performed by comparing the position-versus-time data obtained from the prototype with video analysis data generated using Tracker software. This comparison indicated that the prototype exhibits good initial performance as a measuring device. Nevertheless, the calibration conducted remains limited as it focused primarily on motion pattern agreement; thus, a more comprehensive accuracy evaluation is required in future studies.

Pedagogically, this prototype has the potential to support more investigation-based physics learning. Integrating the apparatus with Investigative Science Learning Environment (ISLE) worksheets enables students not only to observe motion phenomena but also to directly acquire experimental data, interpret data patterns, establish position-versus-time functional relationships, and represent experimental outcomes graphically. Consequently, the apparatus serves not merely as a measuring instrument, but as an instructional medium that assists lecturers or instructors in guiding students toward more active, data-driven, and inquiry-oriented scientific activities.

Another implication of this prototype development relates to device usability in introductory physics laboratories. Direct data display via a mobile application allows students and instructors to monitor experimental results with greater ease. This feature reduces the time traditionally spent on manual data logging, providing students with greater opportunity to focus on data interpretation, graphical analysis, and conceptual discussion. Therefore, this prototype offers an alternative laboratory apparatus that supports linear motion learning in a more interactive, flexible manner tailored to the needs of physics education laboratories.

From a device development perspective, this prototype demonstrates potential as a relatively low-cost laboratory apparatus. Its low-cost nature stems not only from the use of affordable electronic components, such as the NodeMCU ESP8266 and HC-SR04 ultrasonic sensor, but also from an in-house manufacturing strategy utilizing 3D printing. The majority of mechanical components—such as the track, moving cart, sensor mounts, reflector, pulley housing, and supporting elements—were fabricated using a 3D printer. The track was designed in a modular, interlocking structure with each section measuring 15 cm in length, thereby allowing track length customization according to experimental requirements. The utilization of PLA+ filament provided flexibility in adjusting component geometry, thickness, and print quality to meet design specifications. This approach aligns with prior research demonstrating that 3D printing and open-source hardware support the development of low-cost, flexible laboratory equipment (Bouquet et al., 2017; Zhang et al., 2013, 2016).

Nevertheless, this prototype exhibits several technical and operational limitations. Ultrasonic sensor performance can be influenced by reflector positioning, reflection angle, measurement distance, and object motion stability along the track due to friction effects. Additionally, the IoT-based system requires a stable internet connection for optimal data transmission and monitoring via the Blynk application. From a manufacturing standpoint, 3D print quality can be affected by filament type, layer thickness, infill density, and printer settings. Consequently, standardized printing and assembly protocols must be established to ensure consistent replication quality. Furthermore, the calibration procedure in this study did not encompass testing across variations in distance, velocity, track inclination angle, and environmental conditions. Future research should perform a broader calibration incorporating measurement error analysis such as mean absolute error (MAE) or root

mean square error (RMSE) to evaluate device accuracy more directly. Another limitation lies in the scope of the pedagogical evaluation. While the limited trial provided initial insights into the potential of the apparatus to support student investigation, it cannot conclusively establish overall pedagogical effectiveness due to the small sample size and absence of a control group.

Overall, the development of this prototype demonstrates that integrating an ultrasonic sensor, microcontroller, IoT, mobile application, and 3D-printed components yields a flexible, interactive, and potentially cost-effective one-dimensional linear motion experimental apparatus. For physics lecturers and instructors, this apparatus can be utilized to support investigation-based laboratory activities, assist students in acquiring direct experimental data, and foster more meaningful analysis of position-versus-time relationships and graphical representations.

4. Conclusion

This study yielded a prototype of an Internet of Things (IoT)-based hands-on experimental apparatus for one-dimensional linear motion experiments. The prototype integrates an HC-SR04 ultrasonic sensor, a NodeMCU ESP8266, the Blynk application, a modular track, an electric pulley system, and 3D-printed mechanical components. The apparatus is capable of recording and displaying object position data in real time while generating motion patterns aligned with the characteristics of one-dimensional linear motion. The pedagogical implication of these findings is that the prototype can assist instructors in designing more efficient laboratory activities, as experimental data can be acquired and monitored in real time. Furthermore, the developed apparatus can be utilized to support investigation-based laboratory sessions that offer students opportunities to engage more actively in the scientific process, shifting laboratory activities from concept verification alone toward strengthening science process skills and graphical representation.

The deployment of readily accessible electronic components and 3D printing for the majority of mechanical components indicates that this prototype holds potential as a relatively affordable and easily replicable laboratory alternative. This low-cost potential is underpinned by the use of off-the-shelf electronic components such as the NodeMCU ESP8266 and HC-SR04 ultrasonic sensor alongside an in house manufacturing strategy employing 3D printing. Most mechanical components including the track, moving cart, sensor mounts, reflector, pulley housing, and supporting elements can be fabricated in-house using PLA+ filament. The modular, interlocking track design also allows the apparatus to be customized to experimental needs, partially repaired, and reproduced without relying entirely on commercial equipment.

Nevertheless, this study possesses several limitations. From a technical standpoint, ultrasonic sensor performance can be affected by reflector position, reflection angle, measurement distance, object motion stability, and internet connection quality. From an evaluation standpoint, technical calibration remains limited to motion pattern agreement, whereas the pedagogical trial was conducted with a limited number of participants without a control group. Therefore, future research should undertake a more comprehensive calibration, incorporate measurement error analysis, and evaluate the effectiveness of the apparatus using a more robust experimental design and a larger participant.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

The authors would like to thank the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia for the funding provided through the DRTPM 2025 (Thesis Research Scheme), grant number B/17.95/UN34.9/PT/2025.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgement

The authors would like to express their gratitude to the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia for providing financial support for this research. Appreciation is also extended to the students who participated in the limited trial and contributed to the evaluation of the developed prototype.

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