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Design and Development of a Free-Fall Experiment Apparatus Based on a Photodiode Sensor

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Abstract

The integration of technology in education, particularly through sensor- and microcontroller-based experimental tools, has proven effective in enhancing the accuracy and efficiency of science learning. This study aims to design a free-fall motion experiment apparatus utilizing a photodiode sensor and Arduino Nano to improve time and gravitational acceleration measurements. The design includes hardware components (electromagnetic ball release, laser, photodiode sensor, and LCD) and software using the Arduino IDE. Experiments at heights of 0.2 m, 0.4 m, and 0.6 m yielded average gravitational acceleration values of 9.715 m/s², 9.787 m/s², and 9.819 m/s², respectively, close to the theoretical value of 9.8 m/s² with low standard deviations (0.351, 0.323, 0.311) m/s². The sensor's fast response (0.001 milliseconds) demonstrates the tool's effectiveness in minimizing manual error. These findings suggest that integrating a photodiode sensor with an Arduino Nano can produce an accurate and efficient tool for physics experiments. Further development, such as automated height adjustment, is recommended to enhance measurement precision.

Keywords: Free-fall motion; photodiode sensor; gravitational acceleration.

INTRODUCTION

The integration of technology in education has been shown to enhance student participation, motivation, and academic achievement (Oyeleye & Oluwafemi, 2020). Optimal implementation, supported by well-structured instructional planning and adequate resources, contributes significantly to improved learning outcomes (Gui & Ismail, 2024). This aligns with research findings highlighting the pivotal role of technology in modern education (Yaseen et al., 2025). One notable application in science education is the use of sensor and microcontroller-based experimental tools (Santosa & Waluyanti, 2019). A study by Habibi and Buditjahjanto (2024) demonstrates that IoT-based microcontroller training kits are highly effective in enhancing students' comprehension of learning materials.

Free-fall motion is a fundamental physics phenomenon describing the movement of objects under gravity without air resistance (Firdaus et al., 2019). A deep understanding of this concept is crucial in physics education, as it forms the basis for many principles of classical mechanics (Fauzan et al., 2022). However, in practice, free-fall experiments often face challenges, such as inaccuracies in measuring time and distance, which can affect experimental results (Walid & Umar, 2022). The use of simple tools, such as manual stopwatches, frequently fails to provide the precision required to accurately analyze motion dynamics (Maiyena et al., 2018).

To improve accuracy and efficiency in free-fall experiments, the integration of sensor technology and microcontrollers has emerged as a promising solution (Boimau & Mellu, 2019). Photodiode sensors, for instance, can detect rapid changes in light intensity (Yulkifli et al., 2019), making them highly suitable for precise measurements of an object's fall time (Wibowo et al., 2023). These sensors operate by detecting variations in light intensity as an object passes through their path (Tsaqifurrosyid et al., 2020), responding within microseconds (Maulana et al., 2020), thereby yielding significantly more accurate measurements than manual methods (Madona & Pratiwi, 2016). A key component facilitating efficient data processing is the microcontroller, which serves as the central processing unit in this experimental setup (Zulkipli et al., 2023). Microcontrollers such as the Arduino Nano offer rapid data processing and wireless connectivity, enabling real-time data collection and analysis. The adoption of this technology not only enhances experimental data quality but also simplifies data acquisition and analysis (Pratama & Kiswantono, 2023).

However, a major challenge lies in the lack of seamless integration between sensors and real-time data processing systems, leading to delays in experimental analysis (Atani et al., 2019). Additionally, many systems still rely on external software for data processing, increasing complexity for educators and students (Rudianto et al., 2024). Several studies have attempted to develop microcontroller-based lab tools to improve measurement accuracy and efficiency in free-fall experiments (Pratiwi & Fatmaryanti, 2020). Yet, most existing systems utilize conventional microcontrollers like Arduino or Raspberry Pi (Rante et al., 2023), while the application of Arduino Nano as the core component remains relatively underexplored (Kusumah & Pradana, 2019). The Arduino Nano offers advantages in faster processing, wireless connectivity (Fadilla et al., 2020), and superior power efficiency compared to traditional microcontrollers (Fernández-

Ahumada et al., 2019). Furthermore, the integration of photodiode sensors with Arduino Nano for free-fall experiments has not been extensively studied, presenting an opportunity for innovation in designing more efficient and accurate tools (Riyanto, 2021).

This study aims to design and develop a free-fall experiment apparatus based on photodiode sensors and microcontrollers. The primary objectives are to enhance the accuracy of time and distance measurements in free-fall experiments (Harnsoongnoen et al., 2024) and to streamline data collection and analysis through modern technological integration (Tran et al., 2024). The urgency of this research lies in the need for more efficient and precise physics lab equipment (Álvarez-Siordia et al., 2025), ultimately improving students' understanding of free-fall motion concepts (Lestari et al., 2023).

MATERIALS AND METHODS

Materials and Methods

This study is an experimental research project conducted in March 2025. The independent variable in this experiment is the height of the object, which will be varied, while the dependent variables are the time recorded during data acquisition and the gravitational acceleration derived from data analysis. The research consists of several key stages: hardware design, software development, device testing, and data collection.

Hardware and Software Design

The hardware setup includes an electromagnetic ball release mechanism, laser, photodiode sensor, microcontroller, push-button switch, and LCD screen, connected as shown in Figure 1

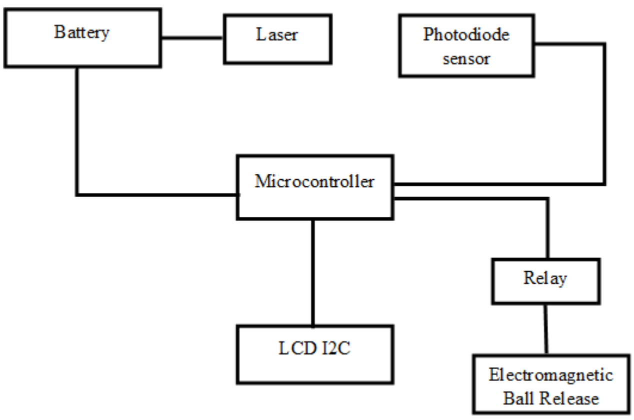

Figure 1. Hardware connection design

The software was developed using the Arduino IDE to implement a program for time data acquisition. The program includes two input buttons: a reset button and a release button. The reset button restarts the time measurement from zero, while the release button activates the ball release mechanism.

Testing and Data Collection

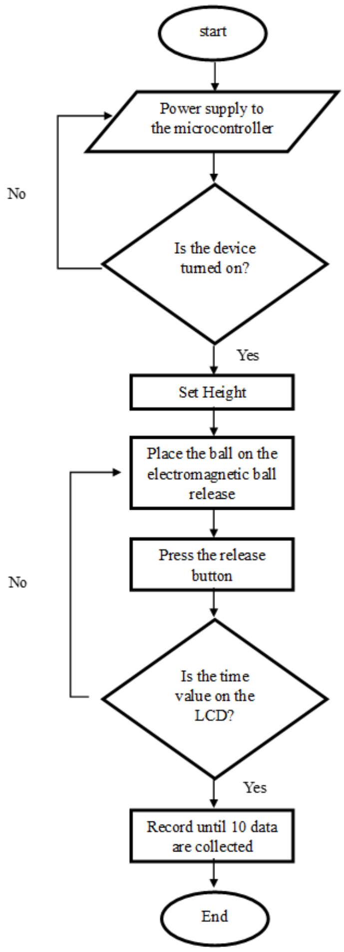

Figure 2. Flowchart of free-fall motion experiment

The study outlines the procedures to be followed when using the free-fall apparatus as shown in Figure 2. This diagram also includes various decision points that must be considered during the experiment's execution. The presence of the flowchart facilitates visualization of the experimental process using the free-fall apparatus.

RESULTS AND DISCUSSION

Result

Device Assembly Result

The development of the free-fall motion experimental device was carried out through several stages, starting from problem identification, system design, component selection, prototyping, and testing and evaluation. This process was guided by the need to produce a practical and accurate tool that can be used in physics learning, especially in understanding the concept of uniformly accelerated motion due to gravity. Various challenges, such as sensor calibration, synchronization between components, and precision in time measurement, were addressed during development. After iterative trials and improvements, a functional prototype was successfully built and tested.

The results of the free-fall motion experimental device developed in this study are shown in Figure 3. This device is designed to improve time measurement accuracy and minimize human error in free-fall experiments. It consists of several integrated hardware components that work synergistically through an Arduino Nano-based microcontroller system.

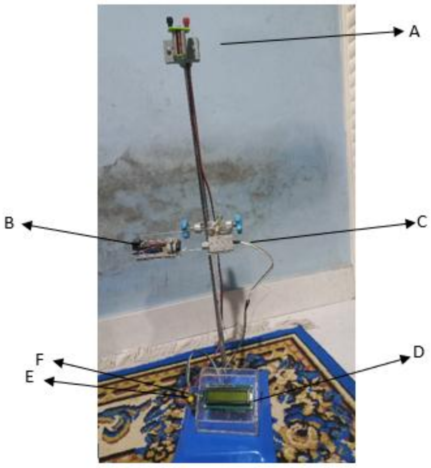

Figure 3. Free fall motion device

The main components of this system include an electromagnetic ball-release mechanism (A), a laser module (B), a photodiode sensor (C), an LCD screen (D), a reset button (E), and a release button (F). The electromagnetic release mechanism functions to hold the iron ball in the initial position and release it precisely when the release button is pressed. The laser module and photodiode sensor are installed facing each other to detect the falling ball. When the ball passes through the laser beam path, the sensor responds to the change in light intensity and records the fall time with high precision.

The LCD screen displays the fall time and the calculated gravitational acceleration results in real time. The reset button is used to reset the system and prepare it for the next experiment, while the release button activates the electromagnetic release and starts the experiment. All these components are controlled by a program written using the Arduino IDE, enabling automatic and real-time data processing.

Experiment results

The experimental data for free-fall motion were collected using a 6-mm-diameter iron ball released from three different heights. Ten trials were performed for each height variation to ensure statistical reliability, as seen in Table 1.

Table 1. Free-fall motion experiment with photodiode sensor.

Height (m)	Fall time (s)	Velocity (m/s)	$g\ (m/s^2)$
0,2	0,199	1,005	10,101
	0,208	0,962	9,246
	0,205	0,976	9,518
	0,199	1,000	10,101
	0,199	1,005	10,101
	0,202	0,990	9,803
	0,204	0,980	9,612
	0,199	1,005	10,101
	0,206	0,971	9,426
	0,208	0,962	9,246
0,4	0,289	1,384	9,578
	0,289	1,384	9,578
	0,290	1,379	9,512
	0,283	1,413	9,989
	0,289	1,384	9,578
	0,280	1,429	10,204
	0,290	1,379	9,512
	0,280	1,429	10,204
	0,290	1,379	9,512
	0,280	1,429	10,204
0,6	0,359	1,671	9,311
	0,352	1,705	9,685
	0,350	1,714	9,796
	0,359	1,671	9,311
	0,344	1,744	10,141
	0,344	1,744	10,141
	0,349	1,719	9,852
	0,349	1,719	9,852
	0,344	1,744	10,141
	0,347	1,729	9,966

As shown in Table 1, the experiment was conducted by dropping an iron ball from varying heights, with 10 trials performed for each height variation. Each trial recorded the time of fall, which was then used to mathematically derive the gravitational acceleration (g) and the object's fall velocity. The velocity was calculated using Equation (1).

$$v = \frac{s}{t} \qquad (1)$$

Subsequently, the gravitational acceleration value for each height will be calculated using Equation (2).

$$g = \frac{2h}{t^2} \qquad (2)$$

Where v is velocity, s is distance, "t" is time, "h" is height, and g is gravitational acceleration. In this experiment, the theoretical reference value for gravitational acceleration is 9.8 m/s², the standard value commonly used in the physics literature. This value represents the acceleration experienced by a freely falling object at Earth's surface due to gravity, assuming no air resistance and standard sea-level conditions.

Based on the results, the highest average gravitational acceleration was recorded at a height of 0.4 meters, with several trials reaching a maximum of 10.204 m/s². This suggests that the experimental setup yielded more stable and accurate time measurements at this height, closely aligning with the standard gravitational acceleration of 9.8 m/s². This was followed by a height of 0.6 meters, where gravitational acceleration values ranged from 9.3 to 10.1 m/s². Although the greater height allows for longer fall times, it also introduces more variation, possibly due to increased air resistance or sensor sensitivity over longer durations. In contrast, the lowest gravitational acceleration values were observed at the 0.2-meter height, with some measurements as low as 9.246 m/s², likely due to the very short fall time, where even minor timing errors significantly impact the accuracy of the calculated g values. In general, the trend shows that as the drop height increases, both the fall time and final velocity increase accordingly, consistent with the laws of free-fall motion. However, the most consistent and accurate measurements of gravitational acceleration were observed at a height of 0.4 meters, making it the most optimal height for this experimental device.

Furthermore, to evaluate the consistency and reliability of the experimental data, the average gravitational acceleration and its standard deviation were calculated for each drop height. These statistical measures provide insight into how closely the measured values align with the theoretical value of gravitational acceleration and the extent of variation observed during the trials, as shown in Table 2.

Table 2. Average gravitational acceleration and standard deviation.

Height (m)	$\bar{g}(m/s^2)$	Standard Deviation (m/s^2)
0,2	9,715	0,351
0,4	9,787	0,323
0,6	9,819	0,311

Table 2 presents the average gravitational acceleration and its standard deviation for each drop height. At a height of 0.6 meters, the average gravitational acceleration was the highest, at 9.819 m/s², accompanied by the smallest standard deviation of 0.311 m/s². This indicates that, despite the longer fall time, the measurements were highly consistent and closely clustered around the mean, suggesting greater reliability at this height. At 0.4 meters, the average gravitational acceleration was slightly lower at 9.787 m/s² with a standard deviation of 0.323 m/s², reflecting good consistency but slightly more variation than at 0.6 meters. In contrast, the 0.2-meter height yielded the lowest average value of 9.715 m/s² and the highest standard deviation of 0.351 m/s², indicating greater variability and lower accuracy, likely due to the shorter fall time, where even minor timing errors have a relatively larger effect on the calculated gravitational acceleration.

Overall, the data suggest that as the height increases, the precision of the gravitational acceleration measurements improves, as reflected by the decreasing standard deviation values. This reinforces the idea that moderate to higher drop heights are more suitable for accurate and reliable measurements in free-fall experiments using this setup.

Discussion

Based on the observational data and calculations presented in Table 2, three experimental values of gravitational acceleration were obtained from varying heights. All three values show a consistent tendency to approach the theoretical gravitational acceleration of approximately 9.8 m/s², as described in classical physics (Giancoli, 1994; Halliday, Resnick, & Walker, 2010; Serway, 2009). This close agreement with the standard value supports the validity of the developed apparatus in producing accurate and reliable measurements. Although minor deviations were observed, they can be attributed to several factors: (1) residual air resistance, which, although minimal, is challenging to eliminate in open-air conditions (Halliday et al., 2010), (2) minor variations in release conditions, such as the exact starting position or angle of the falling object, and (3) sensor and microcontroller limitations, which may introduce small calibration or signal reading errors.

To evaluate the precision and reliability of the results, statistical analysis was conducted using standard deviation, a widely accepted measure of data spread from the mean (Taylor & Thompson, 1998). The small standard deviation values at all three heights (as shown in Table 2) indicate a high level of data consistency, confirming that the measurements were stable and repeatable across trials. This result is also supported by the excellent performance of the photodiode sensor used in the device, which operates with a fast response time of approximately 0.001 milliseconds. Such speed enables precise detection of fall durations, particularly crucial in short-range measurements where timing accuracy directly influences the calculated value of gravitational acceleration. Overall, these findings validate the effectiveness of the experimental setup in conducting fundamental mechanics experiments with high accuracy.

CONCLUSION

The experimental apparatus developed in this study has successfully achieved accurate fall time measurements with a precision of 0.001 milliseconds. The obtained gravitational acceleration values show excellent agreement with theoretical predictions, confirming the system's reliability and proper functionality. This measurement accuracy is further supported by statistical analysis, revealing low data dispersion, indicating high consistency and measurement reliability across all trials. Future iterations could incorporate automated height adjustment mechanisms (e.g., ultrasonic rangefinders with stepper motor actuators) to eliminate manual positioning errors, potentially reducing measurement variance for educational laboratory applications.

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