



Design, Implementation, and Performance Evaluation of a Simple Pendulum Dynamics Experimental System Based on Arduino

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ABSTRACT

This study presents the design, implementation, and evaluation of an Arduino-based system for simple pendulum experiments. By integrating an electronic control system with an infrared sensor, the instrument minimizes human-operation errors and environmental fluctuations, thereby enhancing measurement performance. Experiments using two string lengths (0.2 m and 0.4 m) and both automatic and manual methods show that the electronically controlled system provides superior accuracy and consistency. The automatic measurements produced a maximum period deviation of only 0.01 s, compared to 0.38 s and 0.30 s manually, with gravitational acceleration deviations as small as 0.02 m/s² and 0.01 m/s². These results confirm the system's improved precision and reliability, demonstrating its effectiveness as a tool for physics experiments and technology supported learning.

Keywords: Infrared Sensor; Simple Pendulum Experiments; Electronic Control System; Arduino Based System.

1. Introduction

Simple harmonic motion is a fundamental physical phenomenon used to analyze various parameters of periodic motion. The regular back-and-forth movement through the equilibrium point produces constant oscillations within each unit of time. One practical example of this phenomenon is the simple pendulum, a mass attached to a string that is capable of oscillating periodically. When the pendulum is released from its equilibrium position, it undergoes forward backward oscillations for a certain duration in accordance with the laws of simple harmonic motion. Through simple pendulum experiments, several parameters such as the oscillation period, string length, and gravitational acceleration can be quantitatively analyzed, making this experiment a common instructional medium for understanding the fundamental concepts of oscillatory mechanics [1], [2]

With advancements in technology, experimental methods for studying simple harmonic motion such as pendulum oscillations can now be performed using more modern and accurate approaches through the utilization of microcontrollers [3]. The use of devices such as Arduino enables automated data acquisition and system control, allowing measurements of oscillation period, angular displacement, and oscillation frequency to be recorded with high precision [4]. This approach not only enhances experimental efficiency but also reduces human errors that commonly occur during manual measurements using a stopwatch [5]. This demonstrates that the integration of microcontrollers in physics experiments, particularly in the study of simple harmonic motion, provides added value to both the learning process and research activities [6].

In the context of physics education, laboratory activities play a crucial role in strengthening students conceptual understanding of natural phenomena [7]. One of the fundamental topics widely explored in mechanics laboratories is the dynamics of a simple pendulum, as this system clearly illustrates the relationship between force, energy, and oscillatory motion [8]. However, manual

measurement of the pendulum's oscillation period often results in errors due to human reaction limitations and the constraints of conventional measuring tools such as a stopwatch [9].

To improve measurement accuracy and efficiency, a technology-based experimental system capable of recording data automatically is required. The use of optical sensors, infrared sensors, or ultrasonic sensors integrated with Arduino has been shown to produce more precise oscillation data [10]. As an open-source platform, Arduino offers high flexibility for integration with various types of sensors and analytical software [11], [12].

In addition, the implementation of microcontroller-based experimental systems provides significant educational value because it offers students hands on experience in designing, programming, and operating digital instrumentation systems. Such project based learning supports the development of 21st century skills, including critical thinking, problem solving, and collaboration [13].

Previous studies have demonstrated that the integration of Arduino in physics experiments can enhance students' learning motivation and active engagement [14]. For example, a pendulum timing system employing photodiode sensors and Arduino showed a measurement deviation of less than 1% compared to manual methods [15]. This confirms that automated systems can deliver more accurate results and can be easily replicated across various educational institutions [16].

Furthermore, the application of automation systems in laboratories supports cost efficiency and promotes the development of locally engineered experimental tools. With relatively low cost, Arduino can be used to develop experimental systems with capabilities comparable to those of expensive commercial laboratory equipment [17]. This is particularly relevant for schools and universities in Indonesia that continue to face limitations in physics laboratory facilities.

This study aims to design and implement an Arduino-based microcontroller system for simple pendulum dynamics experiments that can automatically measure oscillation periods and display the results digitally. The system is expected to improve the efficiency of physics laboratory activities, provide more accurate experimental data, and serve as a technology based interactive learning medium aligned with the direction of digital education transformation [18], [19].

2. Method

The device design method is divided into two stages, namely the electronic system design and the structural and layout design of the apparatus.

A. Stage I

The first design stage was carried out by identifying the required device components according to the design objectives. Based on the component identification, the following components are needed:

1. A power supply, functioning as the main power source for all parts of the circuit with input to the Arduino.
2. An Arduino Uno, serving as the controller for the sensor, 16×2 LCD, and push-button switch.
3. Proximity sensor, used to detect the number of pendulum oscillations. The specification used is an E18-D80NK infrared proximity sensor, with electrical characteristics including a sensing distance of 3–80 cm, an object detection type of opaque/non-transparent objects, and a 5 V dc supply voltage. Its technical parameters include a dc output current / relay output of 100 mA / 5 V power supply, dc current consumption <25 mA, and a response time of <2 ms.
4. A 16×2 LCD, functioning to display data including the set point, string length, oscillation period, and gravitational acceleration value.

The block diagram of the device can be seen in Figure 1 below:

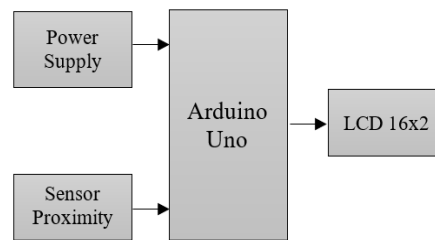


Fig. 1. Device Block Diagram

From the block diagram, the components of the device that function as input, process, and output elements can be identified. The components that serve as inputs are the power supply and the proximity sensor. The component designed to function as the process controller is the Arduino Uno. Meanwhile, the component that serves as the output or result is the LCD.

Based on the block diagram, the hardware and software development processes were carried out beginning with the initial step of connecting the Arduino Uno with the proximity sensor.

A.1. Hardware Development

After completing these processes, the overall circuit configuration is obtained, as shown in Figure 2 below:

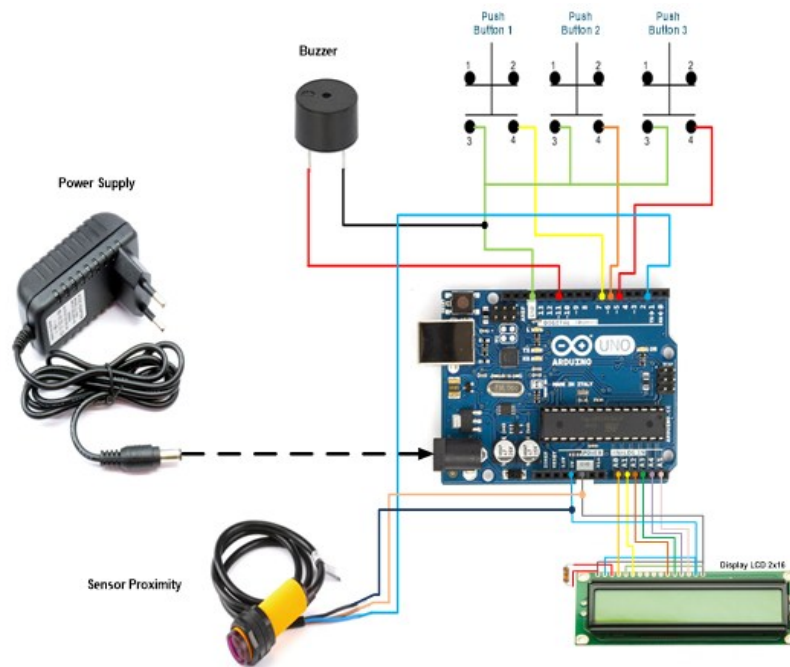


Fig. 2. Overall Circuit Diagram

A.2. Source Code Development

The process of inputting the source code into the software embedded in the Arduino Uno enables the device to operate as a Simple pendulum dynamics experimental system for calculating gravitational acceleration

B. Stage II

The second design stage is carried out by identifying the dimensions and functions of the device to ensure that the layout supports optimal system operation.

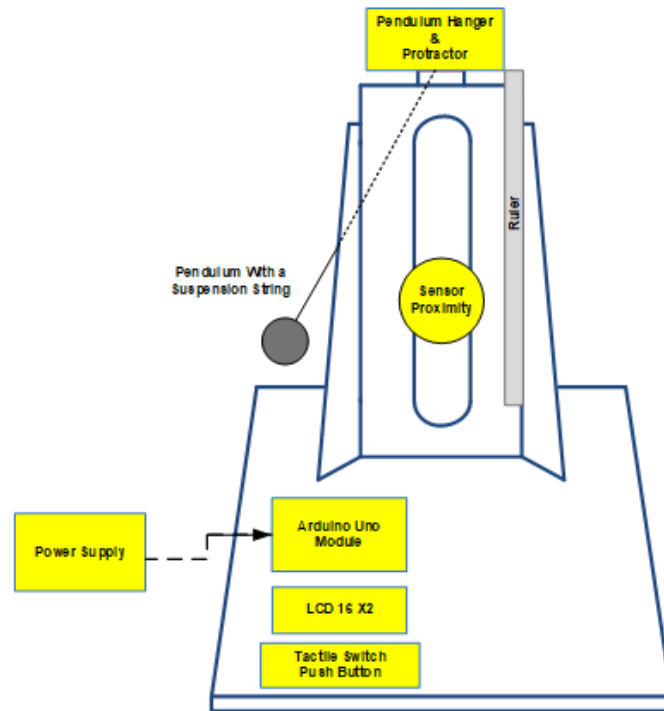


Fig. 3. Component Layout

C. Stage III

The experimental procedure for the Arduino-based Simple Pendulum Dynamics System is carried out as follows:

1. Connecting the power supply to the PLN electrical outlet and attaching the DC adapter to the Arduino module. Once the system is activated, the experimental variables are set as follows:
 - a. The string length (L), starting from 0.2 meters and 0.4 meters.
 - b. The number of oscillations (n), set to 10 cycles.
2. Pulling the pendulum bob to an initial displacement angle of 15° without applying any additional force, then releasing it.
3. Observing the counting process performed by the Arduino. The buzzer sounding each time the pendulum passes the sensor indicates successful detection.
4. After the specified number of oscillations is reached (indicated by a longer buzzer sound), the measurement results can be displayed by pressing push button 2, followed by button 1 or 3 to display the oscillation period and the gravitational acceleration.

The formula used to calculate the period value is as follows:

$$T = \frac{t}{n} \quad (1)$$

Description:

T = Period

t = Pendulum Oscillation Time

n = Oscillation Count

The formula used to calculate the gravitational acceleration value is as follows:

$$g = 4.(\pi)^2 \cdot \frac{L}{T^2} \quad (2)$$

Description:

g = Gravitational Acceleration (m/s^2)

L = Pendulum String Length (m)

T = Period (s)

$\pi = 3,14$

3. Results and Discussion

The results of the device design can be seen in Figure 4 below. The Arduino Microcontroller-Based Simple Pendulum Dynamics Experimental System is capable of automatically calculating gravitational acceleration without human intervention, thereby eliminating potential human and environmental errors, including the following:

- Errors in counting the number of pendulum oscillations, causing the stopwatch reading to be either greater or smaller than the actual value.
- Alignment between the initial pressing of the stopwatch and the moment the pendulum is released by hand.
- An uneven surface on which the apparatus is placed.
- External forces such as wind or vibrations originating from other objects.



Fig. 4. Device Design Results

Subsequent testing is carried out to assess the operational performance of the Arduino-based simple pendulum system. In this stage, the measurement results are compared with those obtained from a manually operated simple pendulum. The primary parameter evaluated in this experiment is the pendulum's oscillation period.

Table 1. Results of Test 1 with a string length of ($L = 0.2$ m) and a displacement of 10°

No	Number of Oscillations (n)	Time (t)	Period (T) $T=t/n$	T^2	Gravity (g)
1.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
2.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
3.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
4.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
5.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
6.	10	9,79 s	0,97 s	0,9584 s ²	8,23 m/s ²
7.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
8.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
9.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²
10.	10	9,79 s	0,97 s	0,9584 s ²	8,23 m/s ²

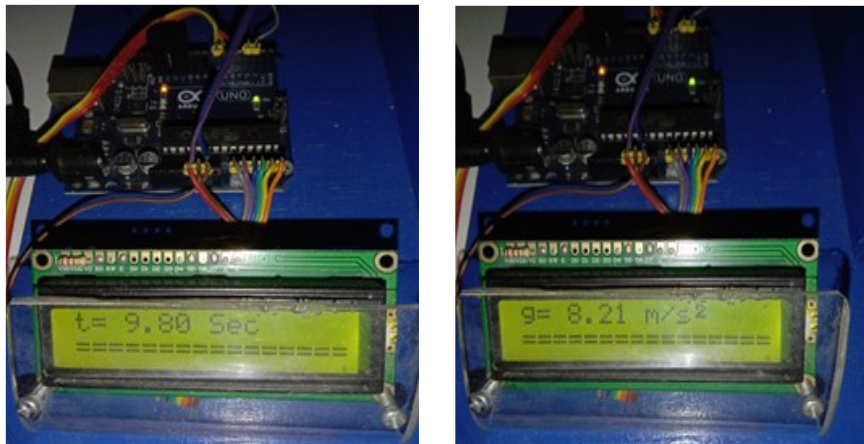


Fig. 5. LCD Display View in One of the Test 1 Measurements

Table 2. Results of Test 3 with a string length of ($L = 0.2$ m) and a displacement of 10° , measured manually

No	Number of Oscillations (n)	Time (t)	Period (T) $T=t/n$	T^2	Gravity (g)
1.	10	9,79 s	0,979 s	0,9584 s ²	8,23 m/s ²
2.	10	10,01 s	1,001 s	1,0020 s ²	7,87 m/s ²
3.	10	9,84 s	0,984 s	0,9683 s ²	8,14 m/s ²
4.	10	10,01 s	1,001 s	1,0020 s ²	7,87 m/s ²
5.	10	9,79 s	0,979 s	0,9584 s ²	8,23 m/s ²
6.	10	10,01 s	1,001 s	1,0020 s ²	7,87 m/s ²
7.	10	9,63 s	0,963 s	0,9274 s ²	8,51 m/s ²
8.	10	9,98 s	0,998 s	0,9960 s ²	7,92 m/s ²
9.	10	9,84 s	0,984 s	0,9683 s ²	8,14 m/s ²
10.	10	9,80 s	0,98 s	0,9604 s ²	8,21 m/s ²

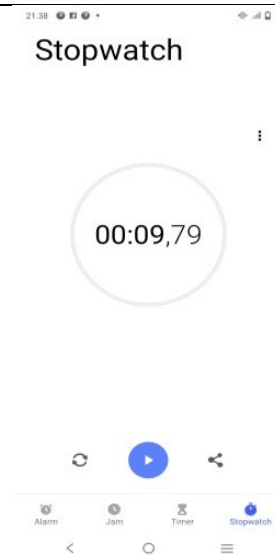


Fig. 6. Display of the Manually Operated Stopwatch in One of the Test 1 Measurements

Table 3. Results of Test 2 with a string length of ($L = 0.4$ m) and a displacement of 10^0

No	Number of Oscillations (n)	Time (t)	Period (T) $T=t/n$	T^2	Gravity (g)
1.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
2.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
3.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
4.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
5.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
6.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
7.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
8.	10	13,20 s	1,32 s	1,7424 s ²	9,05 m/s ²
9.	10	13,20 s	1,32 s	1,7424 s ²	9,05 m/s ²
10.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²

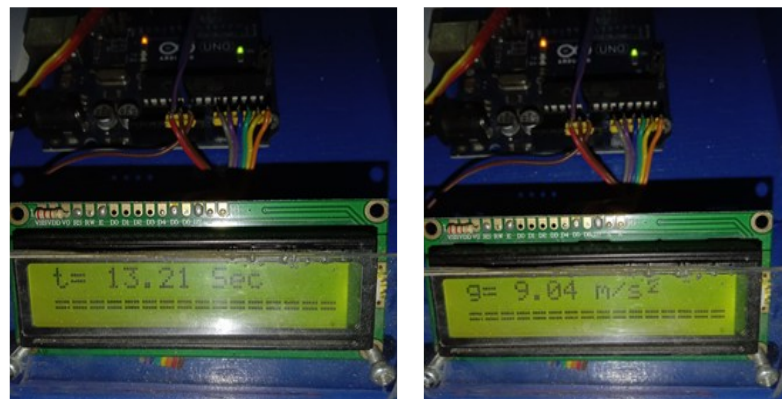


Fig. 7. LCD Display View in One of the Test 2 Measurements

Table 4. Results of Test 3 with a string length of ($L = 0.4$ m) and a displacement of 10° measured manually

No	Number of Oscillations (n)	Time (t)	Period (T) $T=t/n$	T^2	Gravity (g)
1.	10	13,21 s	1,321 s	1,7450 s ²	9,04 m/s ²
2.	10	13,24 s	1,324 s	1,7529 s ²	8,99 m/s ²
3.	10	12,98 s	1,298 s	1,6848 s ²	9,36 m/s ²
4.	10	13,17 s	1,317 s	1,7345 s ²	9,1 m/s ²
5.	10	13,20 s	1,32 s	1,7424 s ²	9,05 m/s ²
6.	10	13,26 s	1,326 s	1,7583 s ²	8,97 m/s ²
7.	10	12,96 s	1,296 s	1,6796 s ²	9,39 m/s ²
8.	10	13,20 s	1,32 s	1,7424 s ²	9,05 m/s ²
9.	10	13,15 s	1,315 s	1,7292 s ²	9,12 m/s ²
10.	10	13,20 s	1,32 s	1,7424 s ²	9,05 m/s ²

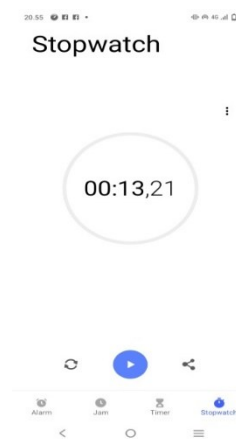


Fig. 8. Display of the Manually Operated Stopwatch in One of the Test 2 Measurements

The performance of the device can be determined by comparing the operation of the designed system with that of the manual instrument. Based on the graph below, it can be observed that the designed device demonstrates better and more consistent performance

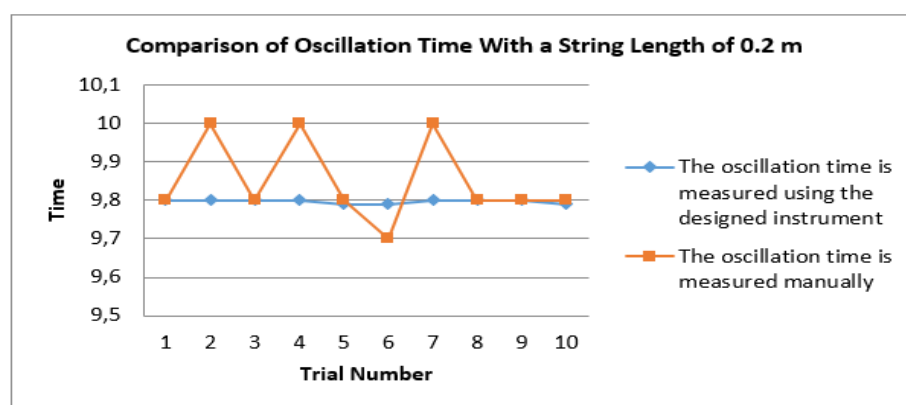


Fig. 9. Comparison of Oscillation Time at a String Length of 0.2 m

The oscillation time measured using the designed device exhibits a higher level of consistency compared to that obtained from the manual instrument. For the string length of 0.2 m, the designed system shows a maximum oscillation time deviation of 0.01 s, whereas the manual device shows a maximum deviation of 0.38 s.

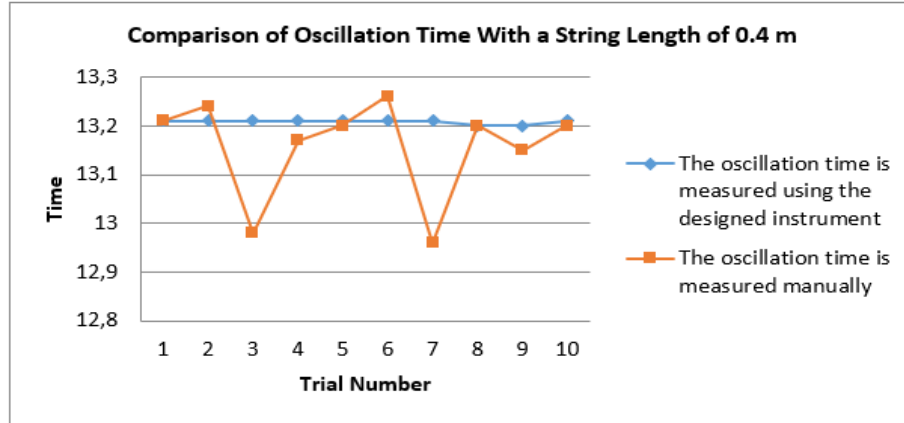


Fig. 10. Comparison of Oscillation Time at a String Length of 0.4 m

In the second experiment, using a string length of 0.4 m, the oscillation time measured by the designed device was more consistent compared to the manual instrument. The maximum deviation in oscillation time recorded by the designed system was 0.01 s, whereas the manual device showed a maximum deviation of 0.3 s.

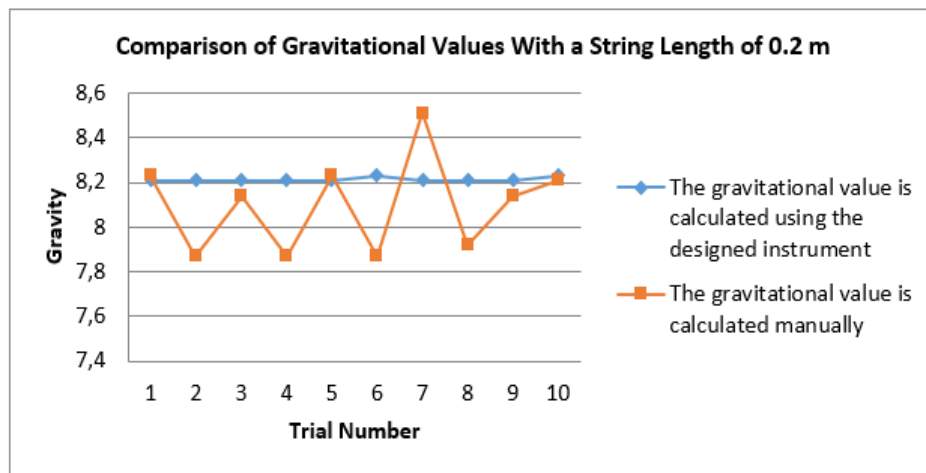


Fig. 11. Comparison of Gravity Values at a String Length of 0.2 m

The gravity values obtained using the designed device exhibit a higher level of consistency compared to those calculated using the manual instrument. The maximum deviation in gravity measured by the designed system is 0.02 m/s², whereas the manual method shows a deviation of 0.64 m/s².

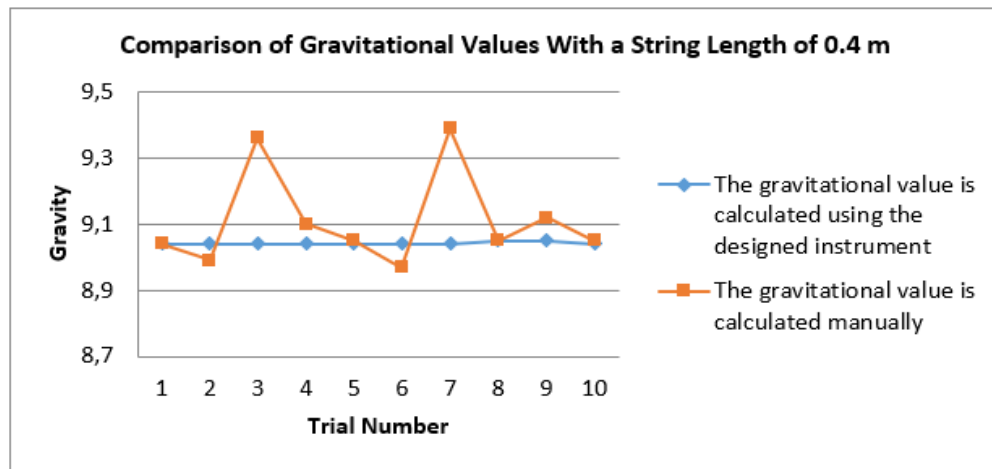


Fig. 12. Comparison of Gravity Values at a String Length of 0.4 m

The second experiment, conducted using a string length of 0.4 m, yielded higher consistency in the gravity values measured by the designed device. The maximum deviation in gravitational acceleration recorded by the system was 0.01 m/s^2 , whereas the manual instrument exhibited a maximum deviation of 0.42 m/s^2 . Based on the tests performed, it can be concluded that the designed device demonstrates superior performance compared to the manual method. The system shows a substantial reduction in measurement error, indicating a markedly improved level of accuracy over traditional manual measurements.

4. Conclusion

Enhancing the performance of measurement instruments can be achieved by integrating an electronic control system that minimizes human-operation errors and reduces the impact of fluctuating environmental conditions. The Simple Pendulum Dynamics Experimental System Based on an Arduino Microcontroller demonstrates these advantages clearly. When compared to manual measurement methods, the electronically controlled system achieves a substantial reduction in measurement errors. Experimental results show that the automatic measurements produce a maximum period deviation of only 0.01 s, whereas manual measurements show deviations of 0.38 s and 0.30 s. Similarly, the automatic calculation of gravitational acceleration yields deviations as small as 0.02 m/s^2 and 0.01 m/s^2 , significantly lower than those obtained manually. These quantitative improvements confirm that the system provides markedly higher precision and reliability than traditional manual approaches.

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