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Travel Time Measurement for Uniformly Varied Rectilinear Motion Based on Infrared Sensor

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ABSTRACT

This study evaluates the accuracy and precision of an infrared sensor system for measuring travel time in uniformly varied rectilinear motion using an Atwood machine. The system employs two IR sensors connected to an Arduino Uno to automatically detect the initial and final positions of the moving mass and record the corresponding travel time. The measured travel times were compared with theoretical calculated from the Atwood-machine acceleration and with measurements obtained using a manual stopwatch. Measurements were performed at seven distances ranging from 0.20 m to 0.50 m with an interval of 0.05 m. The results show an average accuracy of 99.31% when the sensor measurements are compared with theoretical, corresponding to an average percentage error of 0.69%. Comparison with stopwatch measurements gives an average accuracy of 96.95% and an average percentage error of 3.05%. Repeated measurements at distances of 0.20 m and 0.30 m produced consistent travel times, with a relative error of 0.17%. These results indicate that the IR sensor-based timing system can measure travel time accurately and consistently while reducing timing errors associated with manual stopwatch operation.

1. INTRODUCTION

Measurement is a crucial process in experiments aimed at determining the quantitative value of a physical quantity [1]. A measurement process requires consistency across repeated measurements to be considered a good or consistent process [2]. Accuracy and precision are two distinct characteristics of measurement results. Accuracy refers to the closeness of a measurement result to a reference value, whereas precision relates to the closeness or agreement among repeated measurement results [3].

An infrared (IR) radiation sensor operates by utilizing infrared signals to detect an object [4]. This sensor can detect the presence of obstacles, object movement, or heat emissions from an object. Generally, an IR sensor consists of two main components: an IR transmitter that emits infrared light and an IR receiver that captures the infrared light reflected by the object. Changes in the signal received by the IR receiver are processed into an output indicating whether or not an object has been detected [5]. In physics experiments, infrared sensors can also be used to automatically detect changes in an object's position over time, enabling the measurement of motion parameters such as velocity [6].

Uniformly Varied Rectilinear Motion is the motion of an object along a straight path with constant acceleration, causing the object's velocity to change uniformly over time [7]. In GLBB, acceleration is defined as the rate of change of velocity with respect to time; thus, the relationship between velocity, time, and displacement can be described using kinematic equations for rectilinear motion, which demonstrate that changes in motion are influenced by the magnitude of acceleration and the duration of the motion [8]. There are two possibilities for uniformly varied rectilinear motion: uniformly accelerated motion (where velocity increases) and uniformly decelerated motion (where velocity decreases). Uniformly accelerated motion is characterized by a velocity that increases over time and positive acceleration [9]. Uniformly decelerated motion is characterized by a velocity that decreases over time and negative acceleration; negative acceleration is commonly referred to as deceleration. Examples of uniformly accelerated linear motion in everyday life include vertical motion (upward and downward) and free-fall motion [10].

Several previous studies have explored the use of sensors to measure motion in physics experiments. One study developed an Atwood machine setup using sensors and an Arduino to automate time measurement and compared the sensor results with those obtained via stopwatch; the findings indicated that sensor-based measurements yielded greater accuracy than stopwatch measurements [11]. Another study utilized IR-LED sensors and TRACKER image processing to investigate motion—specifically uniform linear motion and uniformly accelerated linear motion—on an Atwood machine [12]. These studies demonstrated that sensor technology serves as a viable alternative for the automated acquisition of motion data.

However, previous research has largely focused on developing experimental apparatus or employing various sensing and data acquisition configurations. This study specifically evaluates the performance of a simple two-sensor infrared (IR) timing configuration designed to measure the travel time between two predetermined positions on an Atwood machine. The study's novelty lies in its quantitative evaluation of the low-cost IR-based system's timing performance through direct comparison with theoretical travel times and manual stopwatch measurements across various travel distances. Thus, rather than merely demonstrating the sensors' ability to detect motion, this research evaluates their accuracy and precision as instruments for measuring travel time. The objective of this study is to evaluate the accuracy and precision of an IR sensor-based timing system for uniformly accelerated linear motion using an Atwood machine. It also compares sensor measurements with theoretical calculations and manual stopwatch readings to determine the extent to which automated timing can mitigate the discrepancies associated with manual measurement.

2. METHODS

This study employs an experimental method to evaluate the performance of IR sensors in measuring travel time. The system utilizes an Arduino microcontroller as the central control unit. IR sensor 1 marks the start time, while IR sensor 2 marks the stop time, allowing the travel time to be recorded automatically. The testing phase involves setting up the experimental apparatus, positioning the sensors, recording travel times using both the IR sensors and a stopwatch, and repeating the measurements. The system's block diagram is presented in Figure 1.

Figure 1. System Block Diagram

The components consist of an Arduino UNO acting as the microcontroller and IR sensors serving as object detectors. The IR sensors generate a digital signal when an object passes—with IR sensor 1 marking the start time and IR sensor 2 the stop time—allowing the microcontroller to record the travel time. The IR sensor employed is the FC-51 module, which features an LM393 comparator chip, operates at a voltage of 3–5 V DC, and provides a digital signal output. This sensor module has a detection range of approximately 2–30 cm and includes a potentiometer for adjusting detection sensitivity [13]. The Arduino UNO used is based on the ATmega328P, featuring a 16 MHz clock frequency, 32 KB of flash memory, 2 KB of SRAM, and 1 KB of EEPROM [14]. The board is equipped with 14 digital pins configurable as either inputs or outputs, six of which support PWM functionality. Additionally, the board provides six analogue input pins, a USB connector, a power jack, an ICSP header, and a reset button [15]. The system's circuit design is illustrated in Figure 2.

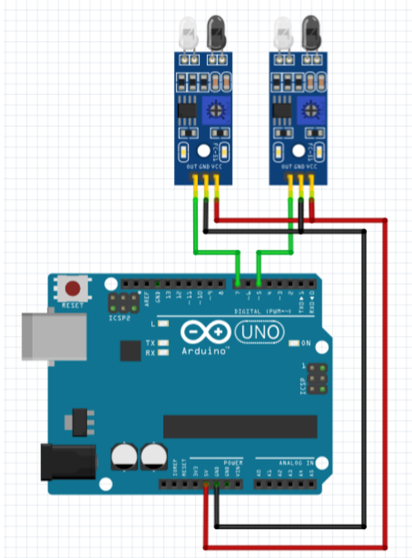

Figure 2. Electronic Circuit Design Results

The software design consists of the plan for providing instructions to and operating the microcontroller—specifically, the operational flowchart shown in Figure 3.

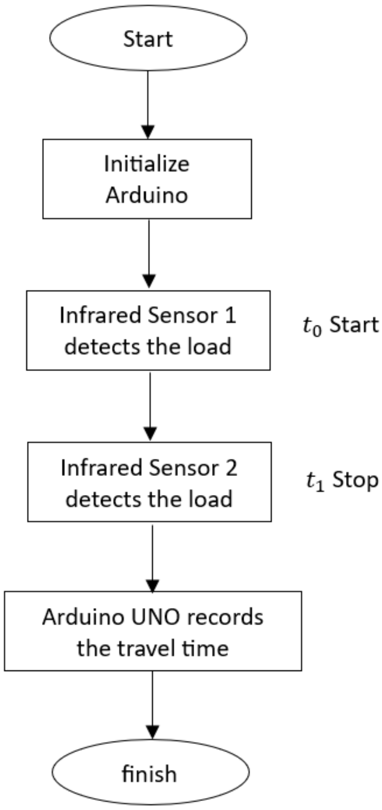

Figure 3. Programming algorithm flowchart

Based on Figure 3, the system starts with system initialization. After the experiment starts, the object moves then IR sensor 1 detects the mass so the start time is recorded then the mass passes through IR sensor 2 and the end time is recorded. Then the Arduino Uno records the travel time and displays it on the Arduino IDE serial monitor. The following mechanical circuit design of the system can be seen in Figure 4.

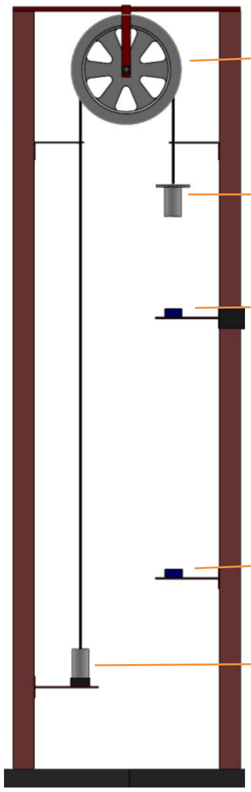

Figure 4. System Mechanics

The experiment was conducted using an Atwood machine consisting of two masses connected by a string passing over a pulley. The mass difference between the two loads generated a net force that caused the system to accelerate. In this study, the masses used were m1 = 107 g and m2 = 115 g, while the pulley mass was 63 g. The pulley had an inner radius of 6 cm and an outer radius of 6.5 cm. The mass and pulley configuration remained constant during data collection, ensuring that any observed changes in travel time were primarily due to variations in the measurement distance. Two FC-51 IR sensors were installed along the path of the masses: IR sensor 1 marked the starting position, and IR sensor 2 marked the ending position. When the mass passed IR sensor 1, the change in the digital signal at the sensor's output pin triggered the Arduino UNO to record the start time. Subsequently, when the mass passed IR sensor 2, the digital signal triggered the recording of the end time. The difference between the end time and the start time was used as the object's travel time. The distance between the two sensors was varied across the following: 0.20 m, 0.25 m, 0.30 m, 0.35 m, 0.40 m, 0.45 m, and 0.50 m.

A series of tests was conducted to evaluate the sensor's performance. These measurements are based on the theoretical acceleration derived from Newton's second law, as expressed in Equation (1).

$$a = \frac{(m_2 - m_1)g}{m_1 + m_2 + \frac{I}{R^2}} \tag{1}$$

And to determine the acceleration value for the measurement of uniformly accelerated linear motion, as expressed in Equation (2)

$$a = \frac{2s}{t^2} \tag{2}$$

The collected measurement data were subsequently evaluated in terms of error rate and accuracy [16]. The error rate was calculated using Equation (3).

$$\%error = \left|\frac{Yn - Xn}{Xn}\right| \times 100\% \tag{3}$$

Where Yn is the travel time value obtained from the stopwatch and theoretical calculations, while Xn is the travel time value from the sensor. Accuracy is measured using Equation (4).

$$Accuracy = 1 - \left|\frac{Yn - Xn}{Xn}\right| \tag{4}$$

3. RESULTS AND DISCUSSION

3.1 Accuracy of Travel Time Measurement

The accuracy of travel time measurements was evaluated by comparing sensor readings against stopwatch timings and the theoretical travel time derived from the acceleration equation (Equation 1). Testing was conducted across seven distance variations—ranging from 0.20 m to 0.50 m at 0.05 m intervals. For each distance, travel time was measured using an IR sensor, and the results were compared with both the theoretical travel time and the stopwatch measurements. Data regarding the accuracy of the IR sensor measurements relative to theoretical are presented in Table 1.

Table 1. Accuracy of Travel Time Measurement between IR Sensor and Theoretical

Distance (m)	t Sensor (s)	t Theoretical (s)	% Accuracy
0.20	1.15	1.14	99
0.25	1.26	1.27	99
0.30	1.42	1.40	98
0.35	1.50	1.50	100
0.40	1.62	1.61	99
0.45	1.70	1.71	99
0.50	1.80	1.80	100
	AVERAGE		99.14

Based on Table 1, the travel time measurements obtained using the IR sensor demonstrate high accuracy relative to the theoretical. The average % accuracy achieved was 99.14%, with an average error rate of 0.69%. The highest error (1.41%) was recorded at a distance of 0.30 m, while the lowest error (0%) was observed at distances of 0.35 m and 0.50 m. Overall, the discrepancy between the measured travel time and the theoretical value was relatively small across all distance variations, indicating that the infrared sensor is capable of measuring travel time with results closely approximating theoretical.

The relationship between distance and travel time also exhibits characteristics consistent with the concept of Uniformly Accelerated Rectilinear Motion. As shown in Table 1, increasing the measurement distance from 0.20 m to 0.50 m resulted in an increase in travel time from approximately 1.15 s to 1.80 s. In GLBB—characterized by constant acceleration and identical initial conditions—the relationship between displacement and time is expressed by the equation $t = \sqrt{(2s/a)}$; consequently, travel time increases as distance increases.

3.2 Comparison of Travel Time Measurement between Infrared Sensor with Stopwatch

To evaluate the performance of the infrared sensor against the manual measurement method, the travel time measured by the sensor was compared with measurements obtained using a stopwatch. Measurements were conducted across seven equal distance intervals, ranging from 0.20 m to 0.50 m in increments of 0.05 m. The comparison between the travel time recorded by the sensor and the stopwatch is presented in Table 2.

Table 2. Accuracy of Travel Time Measurement between Infrared Sensor and Stopwatch

Distance (m)	t Sensor (s)	t Stopwatch (s)	% Accuracy
0.20	1.15	1.15	100
025	1.26	1.20	95
0.30	1.42	1.33	93
0.35	1.50	1.43	95
0.40	1.62	1.51	93
0.45	1.70	1.70	100
0.50	1.80	1.79	99
	AVERAGE		96.42

Based on Table 2, travel time measurements using the IR sensor achieved an average % accuracy of 96.42% compared to stopwatch measurements, with a mean error percentage of 3.30%. The highest accuracy (100%) was observed at distances of 0.20 m and 0.45 m, while the lowest accuracy (93%) occurred at distances of 0.30 m and 0.40 m. The discrepancy between the sensor and stopwatch results was more pronounced at certain distances than the difference between the sensor readings and theoretical.

This discrepancy may be attributed to the stopwatch measurement method, which relies on human response to determine start and stop times. Manual timing can introduce systematic error and random uncertainty due to the operator's reaction time. Faux and Godolphin demonstrated that stopwatch measurements in physics experiments can introduce uncertainty stemming from human reaction to visual stimuli [17]. In the system developed here, timing is recorded automatically as the mass passes infrared sensors 1 and 2; consequently, the recording process does not require operator intervention as the object passes the measurement points. Figure 5 illustrates the comparison of travel time obtained from the sensor, theoretical calculations, and the stopwatch.

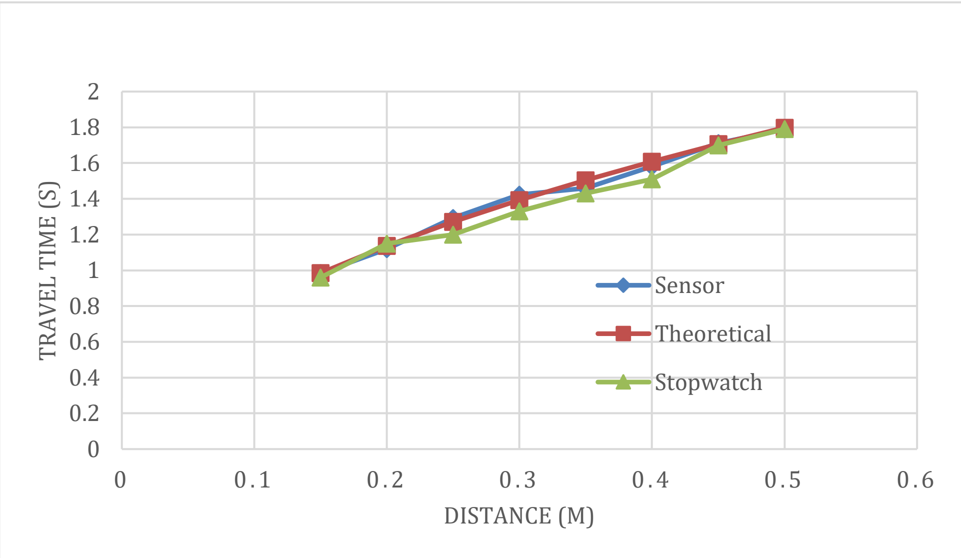

Figure 5. Travel Time Accuracy Test Results

As shown in Figure 5, the difference between the sensor's measured and the theoretical is very small compared to the results obtained using a stopwatch. This indicates that the sensor is capable of measuring travel time with greater accuracy than a stopwatch, as the latter is susceptible to human error, whereas the sensor automatically records the time when the object passes the measurement point. A system is considered to have good precision when its measurement results closely approximate the reference or true value [18].

3.3 Precision of Travel Time Measurement

Measurement precision was determined by performing ten repeated measurements of the travel time recorded by the IR sensor. Good measurement precision is indicated by repeated measurement results that are close in value or consistent with one another [18]. Precision testing was conducted at distances of 0.20 m and 0.30 m, representing the measurement range. These two distances were selected to evaluate sensor reading consistency across a narrow range without presenting the full set of repetition data for every distance variation, thereby keeping the presentation of results concise. The results of the travel time precision tests at these two distances are presented in Table 3 and Figure 6.

Table 3. Precision of Travel Time Measurement

No.	Distance 0.20 m		Distance 0.30 m	
	Time (s)	Precision (%)	Time (s)	Precision (%)
1.	1.10	96.34	1.38	98.55
2.	1.11	97.30	1.39	99.28
3.	1.10	96.34	1.41	99.29
4.	1.11	97.30	1.39	99.28
5.	1.11	97.30	1.40	100
6.	1.10	96.64	1.39	99.28
7.	1.11	97.30	1.40	100
8.	1.11	97.30	1.40	100
9.	1.12	98.21	1.41	99.29
10.	1.11	97.30	1.40	100
Average	1.11	97.10	1.40	99.50

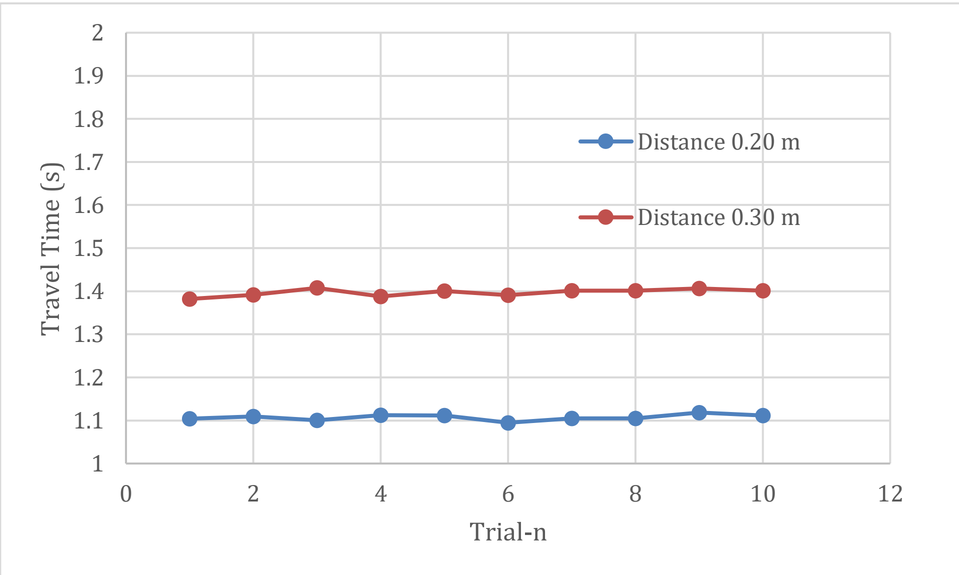

Figure 6. Precision Test of Travel Time Measurement

Based on Figure 6, the travel time precision test results show relatively stable across repeated measurements, with an average precision of 97.10% for a distance of 0.02 m and 99.50% for a distance of 0.03

m. These results indicate that the system is capable of producing consistent time measurements with a relatively small deviation of 0.19%. The relative error observed during testing indicate minimal deviation, demonstrating the infrared sensor's good measurement repeatability. The selection of 0.20 m and 0.30 m distances was not intended to imply that the sensor's precision is limited to only those two distances; rather, they served as representative samples to demonstrate measurement consistency within a close-range span. Accuracy testing (as shown in Table 1) was conducted across the full range of distances from 0.20 m to 0.50 m, allowing for an evaluation of the sensor's ability to produce travel time close to the theoretical throughout the entire measurement range.

4. CONCLUSION

Test results indicate that the system exhibits excellent measurement performance, achieving an average travel-time measurement accuracy of 99.31% relative to theoretical and 96.95% relative to stopwatch measurements. Furthermore, the precision results were consistently high, showing minimal deviation across repeated measurements with a relative error of 0.17%. These findings demonstrate the system's ability to accurately and consistently represent the characteristics of uniformly accelerated linear motion (GLBB) while simultaneously minimizing measurement errors caused by human factors.

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DECLARATIONS

Authorship contribution

Avri Lyana Syafitri: Conceptualization, methodology, formal analysis, software and writing-original draft.
Asrizal and Mona Berlian Sari: Validation, Writing-review and editing.

Competing Interest

The author **declare** no conflict of interest in this study.

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Ethical Clearance

There are no human subjects in this manuscript, and informed consent is not applicable.

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