



Design of a Gravity Acceleration Measurement System of Pendulum Oscillation Modeling Tool and Tracker Video Analysis

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Abstract: Experiment has a crucial role in physics, one of the fundamental science for research and technology. This research focuses on gravitation and utilizes methods of experimental design and execution. Measuring gravitation is a frequently studied topic and related to the oscillation pendulum's harmonic. In practice, pendulum oscillations are often still calculated manually without visualizing the pendulum's trajectory during oscillation. The development of modern learning tools allowed researchers to analyse and calculate using video tracker software to produce a graph as a result. A static pendulum with a string in three lengths: 50 cm, 60 cm, and 70 cm is required. The swinging pendulum loaded with a 100-gram weight and filmed by a camera. The recordings were analysed using the tracker software. The results were displayed as a sinusoidal waveform plotted from the points along the pendulum's path during oscillation to conduct the influence of rope length with period and frequency, so we can see the result of gravity for each variation of rope length like 50 cm with 9.84 m/s^2 with 0.4% of percentage of error, variation of 60 cm with the result 9.87 m/s^2 while having 0.7% of percentage of error, and for 70 cm of variation the result is 9.89 m/s^2 with 0.9 percentage of error.

Keywords: Gravitational Acceleration, Pendulum Oscillation, Digital Imagery, Video Tracker.



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1. Introduction

Physics is based on observation and activities that rely on knowledge about a phenomenon and on prior knowledge or ideas to acquire the information necessary for observational competence. observation is the ability to use senses to gather data or information to identify and determine an object nature or event. In his description of physical reasoning, observational activities or observation, serve as a means to explain cause and effect in empirical findings. Observation is also an important step in investigating processes prior to measurement and data

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processing, leading to inferences in concepts form, principles, and laws that exist in the natural sciences and physics. As a branch of science, physics as an observation-based science that studies objects such as mass, length, time, and their changes, as well as other natural phenomena [1].

Experiments are a central and frequently used tool for developing measurement methods in physics. They serve as a means to an end and play a crucial role in the development and understanding of physics, particularly in measuring fundamental quantities namely gravitational acceleration. When conducting experiments, it is important to pay attention to the methodology and equipment used. Since the majority of learning in the present epidemic period takes place online, conducting a hands-on practicum in a lab will not be challenging. There is currently software called Tracker that enables students to carry out thorough kinematics study. Video analysis techniques about natural phenomena, particularly those pertaining to force, acceleration, speed, velocity, gravitational field, energy conversion, and conservation, are used by this software. [2]. In this context, video tracker technology has established itself as an innovative solution that enables higher precision and better accessibility of experimental measurements. Video tracker allows a highly precise analysis of object motions through digital processing, thus opening up new possibilities for investigating complex physical phenomena such as pendulum oscillations for measuring gravitational acceleration [3]. This technology not only improves measurement accuracy but also expands the possibilities of experiments in laboratories with limited resources, thereby enabling more in-depth analyses [4].

The facts review reveals that outdated methods or manual calculations are still frequently used in information processing within the education environment, for example, in experiments to calculate pendulum oscillations. According to a 2015 study conducted by the Programme for International Student Assessment (PISA), Indonesia's children continue to lag behind international standards in their scientific reasoning skills. Their average score was 403 out of a possible 493 points. In the 2013 PISA results, Indonesia's children improved their ranking by six places, having previously been second to last (69th out of 76 countries) [5]. One factor influencing the results of this study is interpretation difficulty, which often arises in practical exercises involving tables and diagrams. Calculating pendulum motion using a video tracker is an innovative application in physics. The video tracker can serve as an alternative to analysing pendulum oscillations' gravitational acceleration, that visualised by displaying sinusoidal waves during the pendulum's motion. The sinusoidal wave represents the visualisation result of tracker software for measuring gravitational acceleration in a simple pendulum oscillation experiment [6]. Gravity significantly influences the pendulum oscillation experiment, so the velocity of motion is determined by damping forces and air resistance [7].

This research develops a method for measuring pendulum oscillations gravitational acceleration using tracker video analysis. The method employs a simple pendulum whose oscillations are measured with three different string lengths. The pendulum motion is analysed using tracker software, which enables highly precise acquisition of pendulum position data over time. The use of tracker video increases accuracy compared to conventional methods and also offers ease of use and portability. This is confirmed by Elot et al research, whose results are comparable to those of other tools, applications, and computational methods. The acquired data are statistically and graphically analysed to calculate the gravitational acceleration and assess the measurement uncertainty. Furthermore, tracker offers an advantage of simple and interactive procedures suitable for use in information retrieval systems for everyday scientific applications [7].

A related study that can serve as a reference was conducted by Aisiyah. In it, she calculated gravitational acceleration using the pendulum oscillation method under varying loads (150 g, 75 g, and 35 g) and arrived at a result of 9.75 m/s^2 [8]. However, Aisiyah's study has a limitation because the gravity was calculated manually, i.e., without video analysis. Selvira et al. also investigated spring oscillations using video analysis in 2020. Investigations of damped harmonic oscillations can measure the fluid's viscosity and visualise the results using a video tracker [9]. These results can be compared with previously determined viscosity values, for example, water at $20 \text{ }^\circ\text{C}$ ($1 \times 10^3 \text{ mPa}\cdot\text{s}$), glycerin at $20 \text{ }^\circ\text{C}$ ($1410 \times 10^3 \text{ mPa}\cdot\text{s}$), and oil at $30 \text{ }^\circ\text{C}$ ($200 \text{ mPa}\cdot\text{s}$). Selvira's experiment in 2020 aims to determine the tracker software's accuracy. However, the research lacks information on the data accuracy.

A pendulum with a video tracker enables analysis of oscillations, which is then graphically displayed. In this research, a method for measuring gravitational acceleration was developed based on digital pendulum oscillations' image analysis using video tracker technology. The method employs a simple pendulum with a string adjustable to three lengths (50 cm, 60 cm, and 70 cm). The pendulum's motion is analysed by tracker software, allowing highly precise acquisition of positional data over time. Compared to conventional methods, this approach offers greater accuracy, ease of use, and portability. Data processing includes statistical and graphical analyses to calculate the gravitational acceleration and assess measurement uncertainty. This study aims to develop an efficient and accessible measurement method for educational and research applications and to make a significant contribution to physics quantities of measurement. Based on the description above, the author intends to amend the research title to “Design of a Gravity Acceleration Measurement System of Pendulum Oscillation Modeling Tool and Tracker Video Analysis” This research aims to develop an efficient and accessible measurement method for educational and research applications and to make a significant contribution to the physics measurement quantities.

2. Materials and Method

This study uses the Design and Development Research (DDR) methodology. Design and Development Research (DDR) is a research methodology providing a systematic process for research development. The design and development research (DDR) was conducted in line with a three-part systematic method, which included the analysis phase, the design and development phase, and the assessment phase. Currently, a lot of educational research uses the design and development research approach to test theories and empirically validate studies. This method, commonly referred to as developmental research or development research, is employed in this study to deliberately and practically create and develop a model [10]. It is considered a pragmatic study methodology that empirically validates theories through practice. Hasbullah in 2022 distinguishes between two types of Design and Development Research: Type 1 encompasses products and tools, while Type 2 focuses on research models. In Type 1, the development of products and tools occurs under specific, detailed conditions. Design and Development Research (DDR) can be seen as a connecting element in the research cycle [11]. Its main focus is on building a connecting system that strengthens interaction between conceptualization and evaluation processes. Figure 1 illustrates the central concept of the Design and Development Research framework.

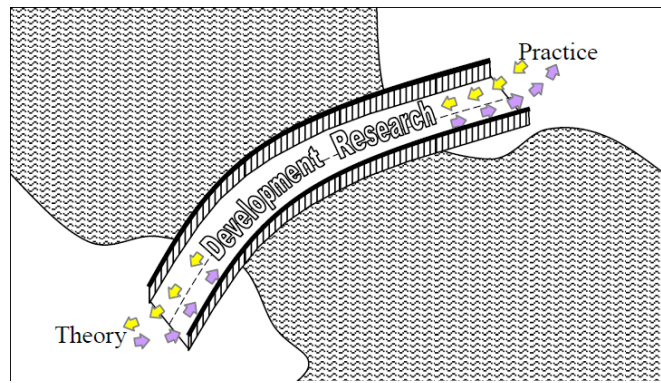


Figure 1. Design and Development Research Framework

Design and Development Research (DDR) if it uses an existing design model and a new process for implementing that model [12]. This also applies if the research utilizes existing tools and applies previously untested tools, models, and methods to a problem in a new system [13]. Likewise, this applies to earlier approaches that have proven effective but exhibit certain similarities, for example, regarding the parameters or sizes used [11]. There are 6 phases of design and development framework, such as; identify the problem, describe the objective, design and the develop the artifact, communicate the testing result, evaluate testing result, and testing the artifact.

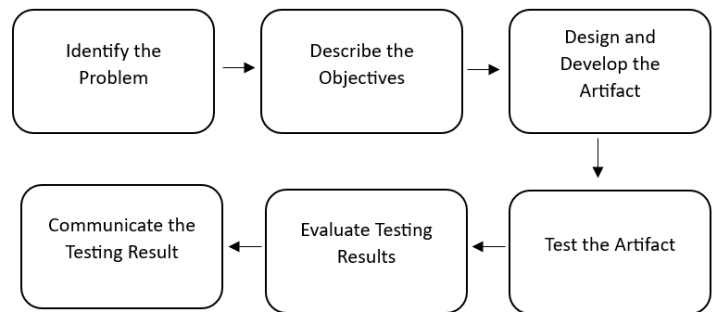


Figure 2. Design and Development Research Stage

This research focuses on calculating the gravity, period, and frequency of a pendulum using conventional methods, such as a pendulum and a stopwatch. Manual data processing presents a challenge [12]. This challenge is addressed in the descriptive objectives by applying the Tracker software to the pendulum analysis. The Tracker software presents the results in the form of graphs and tables containing the period, frequency, and gravity values according to the formula for harmonic oscillation. An important aspect is that the design and testing of the system play a role as tool design, consisting of data acquisition design and software tracker analysis design.

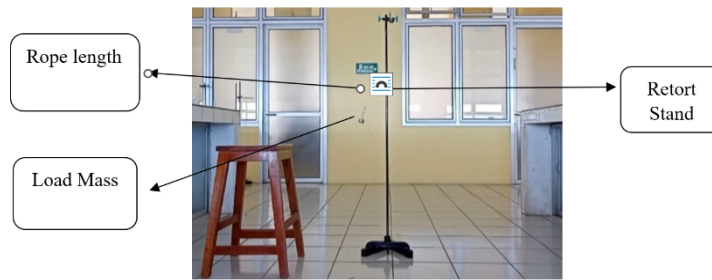


Figure 4. Data Collection Design

Figure 3 illustrates three variables involved in the experimental setup: rope length, load mass, and the supporting stand. In this experiment, the rope length was adjusted to several values, namely 50 cm, 60 cm, and 70 cm, while the load mass was kept constant at 100 grams. The stand functioned as a support to ensure consistent pendulum oscillations throughout the trials. Figure 4 presents the analysis framework carried out using the Tracker software.

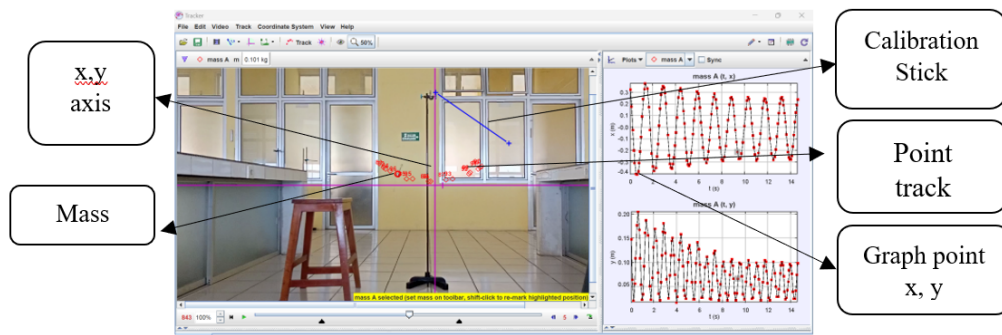


Figure 3. Design of Analysis Using Tracker Software

Figure 4 shows that the tracker's software analysis encompasses various aspects, including the x- and y-axis positions, the load mass, the calibration rod, the trajectory point positions, and the results of the x- and y-graph display. The calibration rod serves as a measurement reference in the video image. The trajectory point positions represent the coordinate points during mass oscillation. The trajectory points are displayed as a sinusoidal wave in the diagram. The x-axis and y-axis, the load mass, and the x- and y-graph display show the object's position over time relative to the x- and y-axis.

3. Results and Discussion

3.1 Research Result

3.1.1 Results of Video Tracker Visualisation for Three String Length Variations

This study uses Tracker software as the central testing tool for three different rope lengths. Tracker's key functions for kinematic analysis are position tracking over time and the calculation and graphical representation of velocity, acceleration, and other kinematic quantities [14]. The recorded pendulum video must first be imported into the Tracker software. Calibration then follows to ensure accurate data acquisition. Tracker has special filters for determining the reference frame and calibration points [14]. Tracker can simultaneously visualise real-world physical phenomena along with their representation in the form of quantitative data and graphs. Figure 4.1

shows the visualization of pendulum oscillations using video Tracker analysis for three different pendulum lengths.

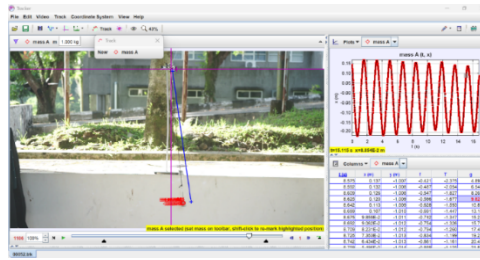


Figure 5. visualization of Tracker Video analysis

Figure 5 shows the video recording output of the pendulum oscillation after applying the analysis menu in the video tracker with the "Sinusoidal Graph" option. These results come from the tracker software that monitors the pendulum's motion. The video tracker records the coordinate points that, according to the selection shown in the figure, generate a sinusoidal graph with peak values. The output consists of a number indicating the x-position over time (t) for 10 pendulum oscillations. The 10 oscillations can be identified by the number of recorded waves. The figure shows 10 peaks and 10 valleys.

Figure 6 presents the displacement–time graph of the pendulum motion obtained from the Tracker video analysis. The graph illustrates a periodic oscillatory pattern, indicating that the pendulum undergoes regular harmonic motion. This visualization is used to analyze key oscillation parameters such as amplitude, period, and frequency.

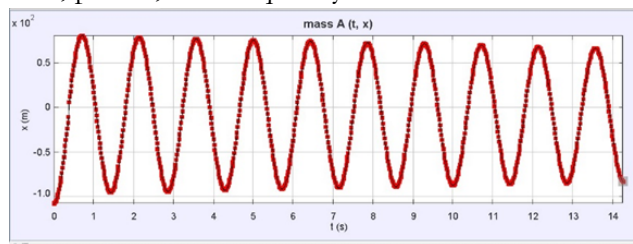


Figure 6. Trajectory of a Pendulum with a String Length of 50 cm

Figure 6 shows the pendulum's trajectory and the measured length changes of the 50 cm long thread, which generates a sinusoidal oscillation. Calculating the oscillation period yields a total time of 14.2 seconds for 10 oscillations and a period of 1.42 seconds. The frequency is 0.70 Hz, as it is inversely proportional to the oscillation period. The amplitude of the wave decreases with increasing oscillation period. The longer the pendulum swings, the smaller the amplitude. This decrease in amplitude is likely due to air resistance's influence [15].

Figure 7 presents the displacement–time graph of the pendulum motion obtained from the Tracker video analysis. The graph illustrates a periodic oscillatory pattern, indicating that the pendulum undergoes regular harmonic motion. This visualization is used to analyze key oscillation parameters such as amplitude, period, and frequency.

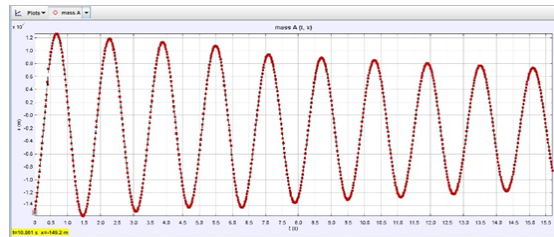


Figure 7. Trajectory of a Pendulum with a String Length of 60 cm

Figure 7 shows the pendulum trajectory and the measured length changes of a 60 cm long string generating a sinusoidal oscillation. Calculating the oscillation period yields a total time of 15.5 seconds for 10 oscillations and a period of 1.55 seconds. The frequency is 0.64 Hz, as it is inversely proportional to the period. This variation exhibits longer period and lower frequency than the variation with a 50 cm string. As with the 50 cm string, the oscillation of the 60 cm string also propagates through the air, influencing the initial and final amplitudes. The initial amplitude in the figure lies between +12 and -14 on the x-axis. The final amplitude of the 10th oscillation lies between +6 and -8. This difference is due to air friction during the vibration.

Figure 8 presents the displacement–time graph of the pendulum motion obtained from the Tracker video analysis. The graph illustrates a periodic oscillatory pattern, indicating that the pendulum undergoes regular harmonic motion. This visualization is used to analyze key oscillation parameters such as amplitude, period, and frequency.

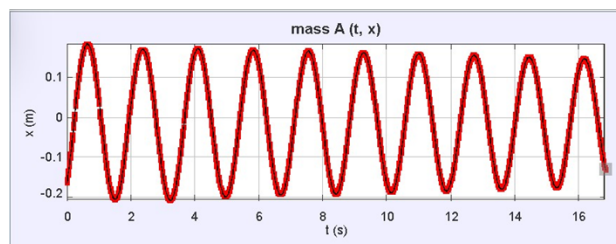


Figure 8. Trajectory of a Pendulum with a String Length of 70 cm

Figure 8 shows pendulum trajectory with measurement results for varying the string length to 70 cm. The oscillation produces a sinusoidal wave with a peak value of 16.8 seconds. Calculating oscillation period yielded a total time of 16.8 seconds for 10 oscillations and a period of 1.68 seconds. The frequency is 0.59 Hz, as it is inversely proportional to the oscillation period. This variation exhibits the longest oscillation period and the lowest frequency compared to all other string length variations. Simultaneously, the frequency is the lowest compared to the 50 cm and 60 cm variations. The longer pendulum string requires a longer oscillation period than the shorter one.

3.1.2 String Length Influence on Pendulum Oscillation's Period

The tracker analysis result for variations of three string lengths was obtained through repeated measurements to determine the accuracy of each measurement deviation. Each string length exhibits a different period for each oscillation. Data acquisition performed by applying a mass with a displacement angle of 10° before the start of the oscillation [7]. The force acting on an object is no longer directly proportional to the displacement when it is large [15]. The acquired data are then analysed with the tracker software to generate a graph representing the pendulum's trajectory

during the oscillation. The tracker software displays two graphs to visualise the trajectory during the pendulum's oscillation [7]. The software also calculates the gravitational force in the harmonic oscillation equation.

Table 1. The effect of string length on the period and frequency of a pendulum

n	50 cm		60 cm		70 cm	
	Period (s)	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)	Frequency (Hz)
1	1.417	0.706	1.548	0.646	1.670	0.599
2	1.417	0.706	1.558	0.642	1.681	0.595
3	1.417	0.706	1.565	0.639	1.680	0.595
4	1.418	0.705	1.549	0.646	1.679	0.596
5	1.414	0.707	1.553	0.644	1.682	0.595
6	1.414	0.707	1.557	0.642	1.675	0.597
7	1.421	0.704	1.554	0.644	1.678	0.596
8	1.415	0.707	1.554	0.644	1.674	0.598
9	1.413	0.708	1.561	0.641	1.680	0.595
10	1.417	0.706	1.551	0.645	1.677	0.596

Table 1 shows research result on string length influence on the period and the frequency of a pendulum. The table illustrates that the period is greater than the frequency and vice versa. This due to the period and frequency are closely related. The frequency is inversely proportional to the period. With a rope length change of 50 cm, the period varies between 1.413 s and 1.421 s, with a mean of 1.416 s. Since the period is inversely proportional to the frequency, the frequency for a rope length change of 50 cm ranges from 0.704 Hz to 0.708 Hz, with a mean of 0.706 Hz. For a rope length change of 60 cm, the period ranges from 1.553 s to 1.565 s, with a mean of 1.555 s. From this data, the frequency recorded by the video tracker was determined, which corresponds to the input formula and lies in the range of 0.639 Hz to 0.646 Hz, with a mean of 0.643 Hz. With a rope length of 70 cm, the period ranges from approximately 1.628 s to 1.680 s, with an average of 1.673 s. Corresponding to the inverse relationship between period and frequency, the frequency lies between 0.595 Hz and 0.598 Hz, with an average of 0.596 Hz.

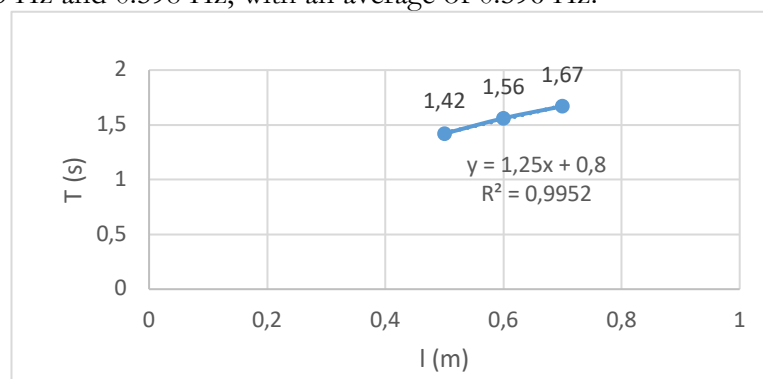


Figure 9. The effect of String Length on the Period

The graph above shows a straight line, indicating that the variable influences the measurement. The line corresponds to the equation $y = 1.285x + 0.777$, resulting in an R^2 value of 0.9978. In this data, the R^2 value is close to 1, meaning that the period is strongly dependent on the string length. The closer the value to the R^2 meaning the stronger the variable's dependence [16]. This means that both the period and the string length are highly correlated. A positive value in the graph indicates that the pendulum oscillation is longer the longer the string.

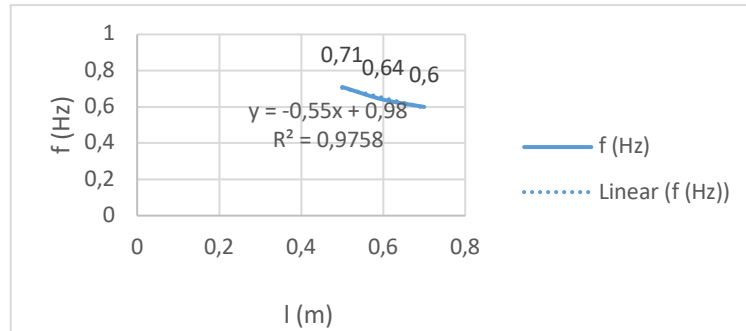


Figure 10. The effect of String Length on the Frequency

The graph above shows a straight line, indicating the variable influence on the measurement. The line corresponds to the equation $y = -0.55x + 0.9783$, resulting in an R^2 value of 0.993. In this data, the R^2 value is close to 1, meaning that the period is strongly dependent on the length of the string. The closer the R^2 value is to 1, the stronger the dependence of the variable [16]. This means that both the period and the string length are highly correlated. A negative value in the graph indicates that the frequency of the pendulum increases with the length of the string

3.1.3 Gravitational Acceleration Measurement System Accuracy and Precision

After the measurements were conducted, the data were processed to determine relative error of the gravitational acceleration measurement system. This analysis was performed to evaluate the reliability of the data obtained using the Tracker software. The data is written in Table 2.

Table 2. Gravitational Acceleration Measurement Relative Error

n	50 cm		60 cm		70 cm	
	g(m/s ²)	Percentage Error (%)	g(m/s ²)	KR(%)	g(m/s ²)	Percentage Error (%)
1	9.84	0.4	9.87	0.7	9.89	0.9
2	9.80	0	9.75	0.5	9.77	0.3
3	9.82	0.2	9.66	1.4	9.78	0.2
4	9.81	0.1	9.86	0.6	9.80	0
5	9.86	0.6	9.81	0.1	9.76	0.4
6	9.86	0.6	9.77	0.3	9.84	0.4
7	9.77	0.3	9.80	0	9.81	0.1
8	9.85	0.5	9.80	0	9.86	0.6
9	9.88	0.8	9.71	0.9	9.79	0.1
10	9.82	0.2	9.84	0.4	9.82	0.2

According to Table 2, the acceleration gravity value (g) for five different rope lengths were determined using the Tracker software. To ensure results' consistency, the measurements were repeated ten times for each variation. The determined gravity values (g) ranged from 9.66 m/s² to 9.89 m/s², with a mean value close to the actual value of the acceleration due to gravity of 9.8 m/s².

For a rope length (l) variation of 50 cm, the gravity value (g) ranged from 9.77 m/s² to 9.88 m/s², with a mean value of 9.83 m/s², a standard deviation of 0.03, and an accuracy of 99.64%. Varying the rope length (l) by 60 cm yielded gravity values (g) between 9.66 m/s² and 9.87 m/s², with a mean of 9.79 m/s², a standard deviation of 0.06, and an accuracy of 99.43%. Variations in rope length of 70 cm showed g -values between 9.76 m/s² and 9.89 m/s², with a mean of 9.81 m/s², a standard deviation of 0.04, and an accuracy of 99.62%. The relative error (%KR) was less than 2% across all variations, indicating high accuracy. These measurements demonstrate that the tracker software provides a precise video-based analysis method for measuring gravitational acceleration.

After the measurements were conducted, the data were processed to determine the precision and accuracy of the gravitational acceleration measurement system. This analysis was performed to evaluate the reliability of the data obtained using the Tracker software. In addition to precision, accuracy was assessed by calculating the degree of data consistency. The measured values obtained from Tracker were then compared with the accepted gravitational acceleration value of 9.8 m/s². The results of the relative error analysis are presented in Table 2.

Table 3. Gravitational Acceleration Measurement Relative Error

No	Rope Length (cm)	Accuracy (%)	Precision (%)
1	50 cm	99,69%	99.66%
2	60 cm	99,90%	99.33%
3	70 cm	99,90%	99.58%

The data show that the pendulum experiment achieves very high measurement quality for all rope lengths, with accuracy values above 99.6% and precision values above 99.3%. At a rope length of 50 cm, the accuracy and precision are both high, indicating close agreement with theory and strong measurement consistency. The highest accuracy (99.90%) is observed at rope lengths of 60 cm and 70 cm, demonstrating minimal systematic error in the experimental setup. However, the precision at 60 cm slightly decreases compared to the other lengths, suggesting a small increase in measurement variability. At 70 cm, the precision improves again, likely due to a longer oscillation period that enhances time-resolution reliability. Overall, the consistently high accuracy and precision indicate that the experimental method is both reliable and suitable for quantitative analysis of simple harmonic motion in a pendulum.

3.2 Discussion

Based on the analysis conducted, the oscillations of the pendulum tool analyzed using Tracker video analysis are consistent with the objectives of this study. The data were processed systematically and presented in the form of tables, figures, and graphs to facilitate interpretation. The comparison of gravity value for each results provided in Table 4.

Table 4. Gravity Value Result with Accuracy of Average

No	Gravity (cm)	Accuracy of Average(%)
1	9,60 m/s ² – 9,92 m/s ²	98.76% [17]
2	9,41 m/s ² – 9,54 m/s ²	96.69% [18]
3	9,66 m/s ² – 9,89 m/s ²	99.43

The results indicate that the Tracker-based analysis demonstrates a very high level of accuracy, as evidenced by an accuracy value exceeding 99.43% across all measurements. These findings are in agreement with the study conducted by Yulkifli, which reported an accuracy level of 98.76% [17]. In addition, research by Setya reported a slightly lower but still high accuracy of 96.69% [18]. The high accuracy values obtained in this study indicate that the Tracker video analysis method is capable of producing measurement results that are very close to the true values. Conceptually, accuracy is a qualitative performance characteristic that expresses the degree of agreement between a measurement result and the value of the measurand. Therefore, a quantitative estimation of accuracy is essential to establish the level of confidence in the results and the reliability of decisions based on those measurements [19].

Precision is also evident in the measurement process of the pendulum analysis using video tracking. In this study, the precision values range from 99.69% to 99.90%, indicating a high level of measurement consistency. These results are in agreement with the findings reported by Fauzi, who obtained a precision value of 94.9% in a pendulum-based experiment [20]. This conclusion is further supported by the study conducted by Mulyadi, which reported precision values in the range of 96–99% [21]. The processing data of video tracker conducted the tracking point for each movement of the mass it tracked by the frame point per second which allowed the result become closer to precision. Overall, these findings confirm that precision refers to the closeness of agreement between independent measurement results obtained under specified conditions [19].

Several limitations were identified during the course of this study. First, data processing based on video analysis requires high camera quality, particularly in terms of image clarity and sharpness, as these factors directly affect the accuracy of the results. Second, the mechanical stability of the experimental setup must be carefully maintained during the recording of the oscillating pendulum, since inadequate static equilibrium can influence the measured period and oscillatory motion. Third, although the Tracker software provides a formula input feature, not all computed results closely approximate the actual value; therefore, this study only considered data that were closest to the accepted gravitational acceleration value of 9.8 m/s².

4. Conclusion

Tracker software is an effective technological tool for physics learning because it enables accurate visual and quantitative analysis of pendulum motion through video tracking. The pendulum's oscillation forms a sinusoidal wave whose amplitude decreases over time, indicating damping. The length of the string significantly influences the oscillation characteristics of the pendulum. A very strong relationship is shown between string length and oscillation period, with a regression value of $R^2 = 0.9978$, meaning that a longer string produces a longer period. Conversely, increasing the string length results in a lower oscillation frequency, as described by the linear equation $y = -0.55x + 0.9783$ with $R^2 = 0.993$. These regression values indicate a strong dependence of both period and frequency on string length. The use of Video Tracker provides higher accuracy and precision than manual methods, with relative errors below 2%. Additionally, the low standard deviation and measurement accuracy above 99% demonstrate the reliability and consistency of the Tracker software in experimental data collection.

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