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COMPARISON OF EXPERIMENTAL DATA GLB AND GLBB USING ROBOTIC LINE FOLLOWER WITH MOTION THEORY

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Abstract :
This study aims to determine the agreement between experimental data from uniform linear motion (GLB) and uniformly accelerated linear motion (GLBB) experiments using a line-following robot and linear motion theory. The novelty lies in providing empirical evidence on the scientific suitability of line-following robots for representing different types of linear motion. The study validates the robot's ability to represent GLB, accelerated GLBB, and decelerated GLBB by evaluating the agreement between experimental and theoretical velocity-time (v-t) characteristics before implementation as a physics learning tool. The method involved conducting linear motion experiments, plotting experimental data on v-t graphs, and comparing them with theoretical graphs. Three types of motion were investigated: GLB, accelerated GLBB, and decelerated GLBB. The accelerated and decelerated GLBB experiments were conducted at elevation angles of 13°, 10°, 7°, and 4°. The results show that the GLB and decelerated GLBB experiments generally align with the corresponding motion concepts. The GLB experiment achieved a mean R^2 value of 1, indicating very high agreement with linear motion theory. Decelerated GLBB achieved a mean R^2 value of 0.8618, with very high agreement at elevation angles of 10°, 7°, and 4°. In contrast, the accelerated GLBB experiment produced a v-t graph inconsistent with theoretical expectations because the robot's speed remained nearly constant rather than increasing uniformly. Therefore, the line-following robot is suitable for representing GLB and decelerated GLBB, particularly at elevation angles of 10°, 7°, and 4°. However, it does not adequately represent accelerated GLBB and requires further modification before use for this motion type.

Keywords: Linear Motion, Line-following Robot, Physics Experiment

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INTRODUCTION

Learning is an interconnected and systematic process consisting of people (teachers and students), resources, facilities, and procedures that play a crucial role in achieving learning objectives (Ilmi & Tajuddin, 2021). Thus, learning can be understood as an effort to create supportive conditions so that the learning process can take place effectively (Ariani et al., 2022). The success of the learning process is influenced by the integration of each of these components in creating meaningful learning experiences for students (Silaban et al., 2022). 21st-century learning must meet high performance standards and involve deep mastery of subject matter to address the complex challenges of our time; these standards apply to all subject areas, including science (Zahroh & Yuliani, 2021). Science emphasizes hands-on learning experiences. Science is the discipline that studies various natural phenomena and occurrences in the surrounding environment through a scientific approach that encompasses scientific processes, products, and attitudes (Kurniati & Suyanta, 2022). Therefore, science education is not only oriented toward conceptual mastery but also toward the development of students' scientific process skills and scientific attitudes (Wardani et al., 2024).

Physics is a branch of science that studies various phenomena occurring in nature and the surrounding environment (Kurniasih & Nugraha, 2023). Concepts, principles, and techniques in physics are applied to disciplines such as chemistry, agriculture, environmental science, and biology to enhance understanding of the characteristics and phenomena being studied (Sudirman et al., 2020). Various concepts in physics are not only theoretical but also have broad applications and can be directly utilized in various aspects of daily life (Supriyatna & Roza, 2021). This is the basis for why science is a required subject from elementary school through college. The topic of motion requires in-depth understanding and is one of the science topics directly related to daily life; therefore, students' mastery of these concepts is crucial (Ellyna Hafizah et al., 2018; Faris et al., 2020).

One topic in the study of object motion is linear motion; linear motion is a fundamental concept in physics that examines the relationship between displacement, velocity, acceleration, and time. At the junior high school level, motion is divided into two categories: uniform linear motion (GLB) and uniformly accelerated linear motion (GLBB). Motion occurs when an object undergoes displacement, influenced by velocity and acceleration (Muzakki et al., 2022). Uniform linear motion is defined as motion that follows a straight-line path at a constant velocity (Kakay et al., 2022). Meanwhile, uniformly accelerated linear motion is motion that follows a straight path with a velocity that changes uniformly (Prasastono & Holili, 2023). There are two types of uniformly accelerated linear motion: uniformly accelerated linear motion, which is characterized by a velocity that increases over time. Uniformly decelerated linear motion is motion in which the velocity decreases over time and eventually comes to a stop (Febriana & Nada, 2021).

The concepts of uniform linear motion (GLB) and uniformly accelerated linear motion (GLBB) are not only understood mathematically but also demonstrated through experimental activities so that students can connect theoretical concepts with real-world phenomena (Dani et al., 2019). In classroom instruction, motion-related material is typically presented only through conventional methods (lectures and tests), resulting in many students still struggling to grasp the basic concepts of motion itself (Ady & Warliani, 2022). Although physics lessons include images to illustrate real-world phenomena such as graphs and motion phenomena, students still struggle to interpret the images they see (Toding et al., 2021). Furthermore, students' lack of understanding stems from the fact that available resources do not sufficiently support their comprehension of the concepts of object motion; their motivation to learn declines over time; and seventh-grade students are not yet very familiar with the material on motion and have relatively low mathematical skills (Maulidina & Khusaini, 2023). Therefore, the concept of motion requires an experimental approach that actively involves students. Through experiments, students are allowed to conduct trials and gain firsthand experience (Abdillah et al., 2020). This active involvement helps students understand learning concepts well because they observe, investigate, and verify the phenomena being studied for themselves (Masus & Fadhilaturrahmi, 2020).

The use of experimental tools is a key factor in supporting the understanding of the concept of linear motion. For example, technology-based experimental tools can help students observe kinematic parameters more concretely and enhance their understanding of motion. Experimental tools that can be used to support learning activities include robots, a technology that enables the integration of science

with other academic disciplines. Robots can support meaningful, in-depth learning and actively engage students in the learning process, which will improve both their understanding and scientific literacy. According to(2023), their research demonstrated that the use of robots as a learning medium has been proven to enhance students' conceptual understanding, active engagement, and scientific thinking skills, as this approach allows students to observe motion phenomena directly, measure velocity and acceleration, and analyze the relationship between force and motion. Therefore, robots serve as learning aids that provide understanding and explanations of motion concepts through direct experience, thereby making it easier for students to grasp motion concepts including uniform linear motion (GLB) and uniformly accelerated linear motion (GLBB) while also helping to improve students' conceptual mastery by directly connecting these concepts to everyday life (Parinduri et al., 2025).

One type of robot that is increasingly being used as a learning tool because it integrates electronics, programming, and engineering into a single hands-on activity is the line-following robot. A line-following robot is defined as a robot designed to follow a predetermined path or line (Kridoyono et al., 2024). The operation of this robot is based on the use of sensors capable of detecting differences in color or contrast levels on the surface of the path, typically utilizing light sensors such as photodiodes or phototransistors (Diva et al., 2024). Various previous studies have shown that the use of robots in education is primarily aimed at improving the quality of the learning process and mastery of robotics skills. Novianta & Firman (2021) Use robots in training to improve students' understanding of robotics technology. Mayub et al. (2023) Report on using robotics experiments in science education and demonstrate their contribution to students' science literacy, while Hidayat et al. (2025) develop a line-following robot as a robotics training tool to enhance understanding of robotics. Arifudin et al. (2024) This study aims to improve teachers' and students' understanding of STEM concepts as well as their skills in integrating educational robotics media into learning. These studies place greater emphasis on robot design and the implementation of project-based learning, whereas research on the ability of line-following robots to represent physics concepts particularly linear motion remains limited. However, previous studies have not specifically investigated whether the motion generated by a line-following robot empirically conforms to the theoretical characteristics of different types of linear motion, particularly GLB, accelerated GLBB, and decelerated GLBB. Unlike previous robotics-based studies that primarily focused on robot development, robotics skills, project-based learning, or educational effects of robotics implementation, the present study focuses on validating the physical motion characteristics generated by a line-following robot. Therefore, the novelty of this study lies in empirically evaluating the robot's ability and limitations in representing these three types of linear motion by comparing experimental and theoretical velocity-time (v-t) characteristics.

Given these circumstances, empirical validation of the line-following robot is necessary before it is recommended as an experimental tool for teaching linear motion. This validation is scientifically and educationally important because an experimental tool should accurately represent the physical characteristics of the concepts being studied. The use of an unvalidated line-following robot may produce motion patterns that differ from the theoretical characteristics of GLB and GLBB, potentially leading students to inaccurate interpretations of the relationship between velocity and time. Therefore, evaluating the agreement between the experimental data generated by the robot and theoretical linear motion characteristics is essential to provide an empirical basis for determining its suitability as an experimental tool physics education.

This study aims to analyze and compare experimental data from GLB and GLBB experiments using a *line-following* robot against the theory of linear motion. The analysis was conducted by comparing the experimental v-t graphs with the theoretical v-t graphs. The fit between the two graphs was assessed based on the coefficient of determination (R^2). R^2 (a measure of how well a linear line fits the data) ranges from 0 to 1 or 0% to 100%; the higher the R^2 value, the better the linear fit of the data (Jasmani, 2021) . The results of the analysis are expected to demonstrate the extent to which the line-following robot can represent the characteristics of GLB and GLBB, while also identifying the factors causing discrepancies between experimental results and theory. This study is expected to serve as a basis for determining the feasibility of using a line-following robot as an experimental tool in teaching linear motion.

RESEARCH METHOD

Equipment and Materials

The equipment used in this study included an Arduino Uno-based *line-following* robot (Specifications: the robot has four wheels two support wheels at the rear and two drive wheels at the front connected to DC motors; the robot weighs 400 grams; 5-channel IR sensor; L298N motor driver; 18650 battery), a track (12 mm plywood covered with white *wallpaper* with a rough surface), a video recorder (*handphone*), and timing *software* (*Tracker Physics*). The materials used for the study were black duct tape (for the robot's path) and track support boards for the inclined plane (GLBB).

Research Variables

In this study, there are three types of variables: independent variables, dependent variables, and control variables. The independent variable is the treatment administered by the researcher; the dependent variable is the aspect measured as the cause-and-effect result of the treatment administered by the researcher; and the control variable is the factor kept constant or the group that does not receive the treatment (Hartono, 2019). The independent variables in this study were the track conditions and the elevation angle. In the GLB, the track was horizontal (0°), while in the accelerated GLBB, elevation angles of 13°, 10°, 7°, and 4° were used, and in the decelerated GLBB, angles of 10°, 7°, and 4° were used. The dependent variables are travel time and robot speed, obtained from video analysis. Control variables include a 2-meter track length, the line-following robot used, robot configuration, motion path, and observation points at 50 cm, 100 cm, 150 cm, and 200 cm. Each experimental condition was repeated three times.

Research Design

This study employs an experimental method to analyze the agreement between experimental data from GLB and GLBB experiments using a line-following robot and the theory of linear motion. The experimental method is a way to determine the effects of applied treatments on the object under study (Ibrahim et al., 2018; Hartono, 2019). The experimental data will be plotted on a v-t graph and then compared with the theoretical v-t graph to determine the degree of agreement. The theoretical models used as references are tailored to the characteristics of each type of motion. In uniform linear motion (GLB), velocity is theoretically constant over time with zero acceleration (a = 0), so the v-t graph is a horizontal line. In uniformly accelerated linear motion, velocity increases linearly with time with positive and constant acceleration, whereas in uniformly decelerated linear motion, velocity decreases linearly with time with negative and constant acceleration. These characteristics serve as the basis for evaluating the motion patterns produced by the line-following robot. This research design focuses on the layout of the experimental setup for a line-following robot for uniform linear motion and non-uniform linear motion.

1. Motion Path Design

The motion track for the robot consists of a flat surface made of 12 mm thick plywood with a length tailored to the requirements. In the center of the track is a straight black line that the robot's sensor will detect to enable it to move in a straight line. The robot's motion track can be adjusted to form an angle of inclination ranging from 0° to 45°. The actual motion track is shown in Figure 1.

Figure 1. Motion track

2. Design of the Line-Follower Robot's Path for Uniform Straight-Line Motion (GLB)

In the GLB experiment, the robot's base is placed on a horizontal plane with a tilt angle of 0˚. The robot's movements will be recorded using a video recorder to produce a video of the robot's motion. The video recorder is included to capture footage during the experiment for travel time analysis. The design of this experimental setup is shown in Figure 2.

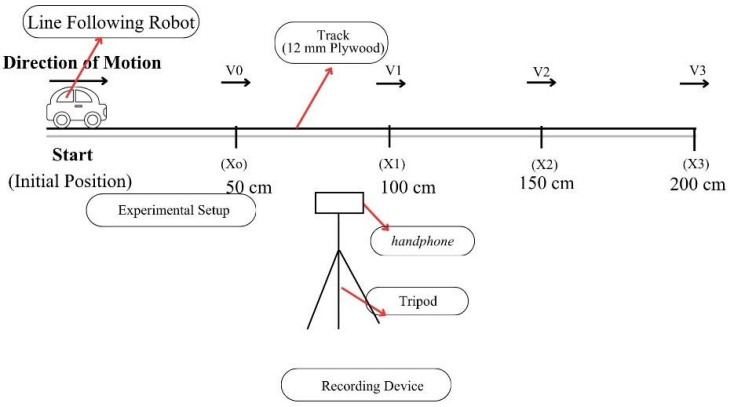

Figure 2. GLB experimental setup

3. Design of the Accelerated Uniform Line-Following Robot (GLBB) Track

In the accelerated GLBB, the robot's movement platform *is set* at a downward incline with elevation angles of 13°, 10°, 7°, and 4°, as shown in Figure 3.

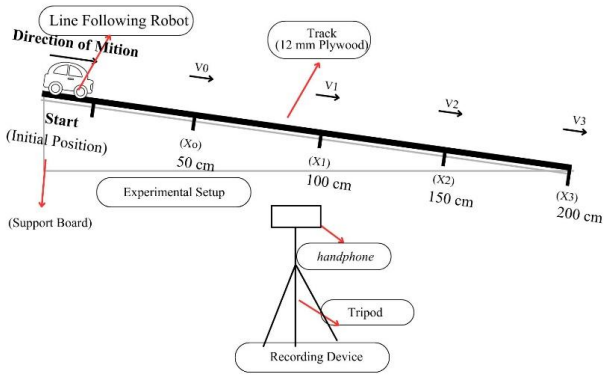

Figure 3. Accelerated GLBB experimental setup

4. Track Design for a Decelerated Uniform Linear Motion (GLBB) Line-Following Robot

In the decelerated GLBB, the robot's movement platform *is set* at upward incline angles of 10°, 7°, and 4°, as shown in Figure 4.

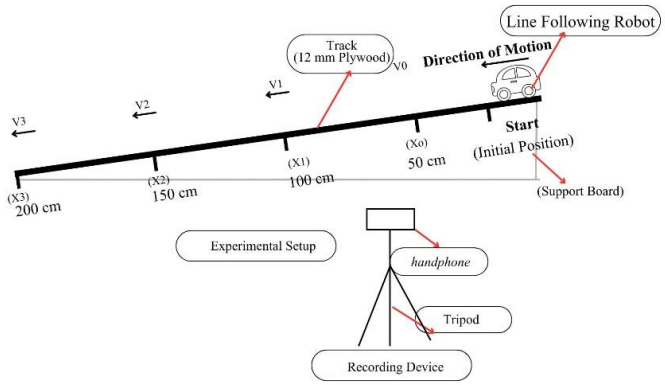

Figure 4. Decelerated GLBB experimental setup

Research Target/Subject

The subject of this study is an Arduino-based line-follower robot used as an experimental apparatus to simulate linear motion. Several variations of the line-follower robot's motion are shown in Table 1.

Table 1. Variations in robot motion

No.	Experimental Group	Repetitions
1	Line-following robot moves in a straight line, with a straight-line path length of 2 meters	3
2	The line-following robot moves using accelerated GLBB, with a path length of 2 meters. Four elevation angle variations: 13˚, 10˚, 7˚, and 4˚.	3
3	The line-following robot moves with decelerated GLBB, with a path length of 2 meters. Three variations in elevation angle: 10°, 7°, and 4°.	3

Research Procedure

This study employed an experimental method. The research procedure is as follows:

a. Prepare the components needed to assemble and build an Arduino *line-following* robot, including the chassis, Arduino Uno R3, 5-channel IR sensor, L298N motor driver, DC motor and gearbox, 18650 battery, a full set of jumper wires, push-button switch, wheels, spacers, solder, solder wire, and screws. The robot assembly steps are shown in the image below.

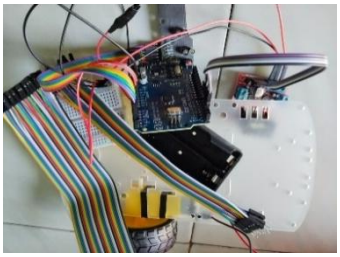

Figure 5. Robot Components

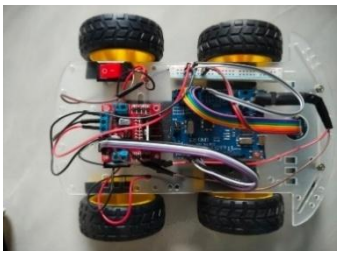

Figure 6. Top Assembly

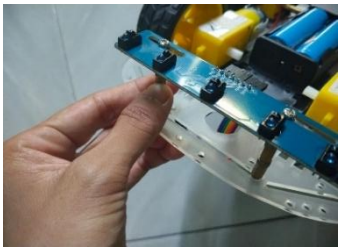

Figure 7. Bottom Assembly

Figure 8. Robot Programming

b. Prepare the robot's track, consisting of a flat track for the GLB experiment and an inclined track with specific angle variations for the GLBB experiment.
c. Conduct preliminary tests on the robot to determine the elevation angle to be used in the data collection process. The tests began at an elevation angle of 15˚.
d. The line-following robot was tested in three experimental groups: GLB, slowed-down GLBB, and accelerated GLBB. The GLB experiment was conducted on a horizontal track (0°). The accelerated GLBB experiment was conducted on a downward-inclined track at elevation angles of 13°,10°, 7°, and 4°, whereas the decelerated GLBB experiment was conducted on an upward-inclined track at elevation angles of 10°, 7°, and 4°. The 13° angle was not used for decelerated GLBB data collection because preliminary testing showed that the robot experienced wheel slippage and was unable to move properly at this inclination. Each experimental condition was repeated three times. Steps for testing the robot in the GLB and

GLBB groups: 1) Place the robot at the starting point (0 m) on a 2-meter-long track and ensure the robot's sensors are functioning properly. 2) Turn on the robot to record video as it moves from the starting position (0 cm) to the end position (200 cm). 3) Analyze the robot video using the *Physics Tracker* app to measure travel time. 4) Record the travel time results obtained from *the Physics Tracker*. 5) Calculate the robot's velocity based on distance and travel time using the velocity formula applicable to linear motion.

e. The experimental results are plotted on a graph of velocity (v) versus time (t) and then compared with the theoretical v-t graph to determine their agreement.

Data Collection and Analysis Techniques

1. Each robot movement was recorded using a *cell phone* camera from a fixed position so that the entire 2-meter trajectory could be seen in the recording. Data collection was performed three times for each experimental group. In the GLB experiment, the trajectory was placed on a horizontal plane, while in the GLBB experiments involving acceleration and deceleration, elevation angles of 13˚, 10˚, 7˚, and 4˚ were used.
2. The experimental videos were analyzed using Tracker Physics software to determine travel time. Measurements were taken at four positions: X_0 (50 cm), X_1 (100 cm), X_2 (150 cm), and X_3 (200 cm). The time was recorded when the robot reached each of these points based on the video recordings. Next, the displacement and travel time data were used to determine the robot's speed at each observation interval.
3. The accuracy of position measurements was determined based on the scale or distance markers used on the track. In contrast, the accuracy of time measurements depended on the temporal resolution of the video recordings analyzed using *Tracker Physics*. Therefore, time accuracy was determined based on the time interval between video frames used in the study. Video-based analysis aimed to reduce the subjectivity of time measurements compared to manual measurements using a stopwatch.
4. The robot's velocity is calculated based on displacement data and the elapsed time at each observation interval. Each experimental condition was repeated three times. For each elevation angle, the velocity data obtained from the three repetitions were averaged at each observation point and used to construct a representative velocity (v) versus time (t) graph. The experimental v-t graphs for each elevation angle were compared with the theoretical v-t graph to determine the degree of agreement between the robot's motion pattern and the theoretical characteristics of GLB and GLBB. Linear regression analysis was performed on the averaged experimental data to obtain the coefficient of determination (R^2) for each elevation angle.
5. The fit of the experimental data to the theoretical model was analyzed using linear regression with the coefficient of determination (R^2). The coefficient of determination (R^2) indicates the extent to which the variation in the experimental data can be explained by the linear relationship between velocity and time. An R^2 value closer to 1 indicates that the experimental data more consistently follow the analyzed model, while a lower value indicates a greater deviation of the data from that model (Amruddin et al., 2022). However, R^2 was not used as the sole indicator of physical agreement. Agreement was also evaluated based on the characteristics and slope of the v-t graph: a slope approaching zero for GLB, a positive slope for accelerated GLBB, and a negative slope for decelerated GLBB. The R^2 values obtained from all elevation angles within each type of motion were subsequently averaged to determine the overall level of agreement between the experimental results and the theoretical characteristics of linear motion. The R^2 value is calculated using the following equation.

$$\text{Average } R^2 = \frac{\sum R^2}{n} \qquad (1)$$

The R^2 value ranges from 0 to 1. The categories of graph fit based on the R^2 value are shown in Table 2.

Table 2. Categories of Graph Fit

R^2 Value	Level of Fit
0.00 – 0.199	Very low
0.20 – 0.399	Low
0.40 – 0.599	Moderate
0.60 – 0.799	Appropriate
0.80 – 1.000	Highly suitable

(Vikaliana et al., 2022)

RESULTS AND DISCUSSION

Results of the Line-Follower Robot Test

1. GLB Test Results

The GLB test data obtained using the line-following robot are presented in the form of a data table and a v-t graph to compare the GLB theory with the test results. The results of the v-t graph comparison are shown in Figure 9.

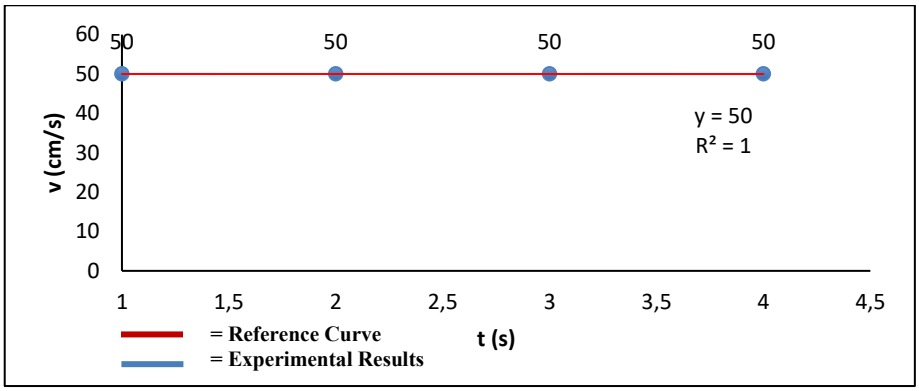

Figure 9. Comparison of the v-t graph of the GLB test results with the theoretical v-t graph

Based on the data in Table 4.2 and Figure 4.1, the comparison of the v-t graphs from the GLB test with the robot shows a regression value (R^2) = 1. This regression value (R^2) indicates the degree of perfection or fit of the obtained linear relationship. The experiments also show that the line-following robot's velocity is constant and has zero acceleration (a = 0). This aligns with the GLB theory, which states that an object's velocity remains constant over a specific time interval with zero acceleration (Za'rah et al., 2024) .

2. Results of the Uniformly Accelerated Linear Motion (GLBB) Experiment

In uniformly accelerated Linear Motion (GLBB), variations in the angle of inclination (elevation) of 13°, 10°, 7°, and 4° were used. In uniformly accelerated Linear Motion (GLBB), variations in the elevation angle were set to 13°, 10°, 7°, and 4°. These four angles were determined based on the results of preliminary tests conducted earlier. Based on the results of the initial test starting at a 15° angle, the line-following robot experienced slippage (skidding) during accelerated GLBB. During decelerated GLBB at angles of 15° and 13°, the robot experienced slippage (the wheels spun in place). Therefore, a maximum angle of 13° was used for accelerated GLBB and a maximum angle of 10° for decelerated GLBB.

a. Accelerated GLBB (Downward Path)

For the accelerated GLBB, several experiments were conducted on an inclined plane with four variations in elevation angle, namely 13°, 10°, 7°, and 4 °. The experimental results are shown below (red indicates the theoretical v-t graph and blue indicate the experimental v-t graph).

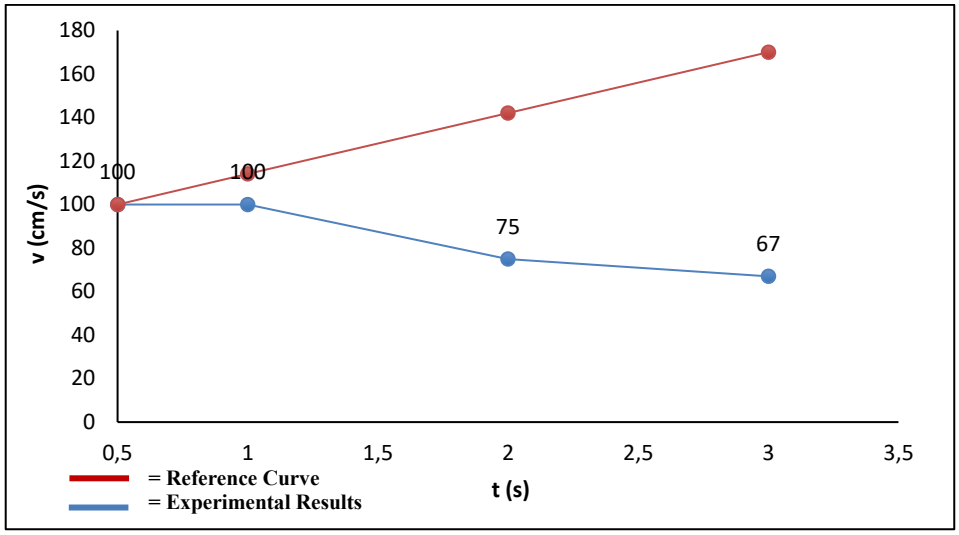

Figure 10. Comparison graph of v-t for the accelerated GLBB at an elevation angle of 13°

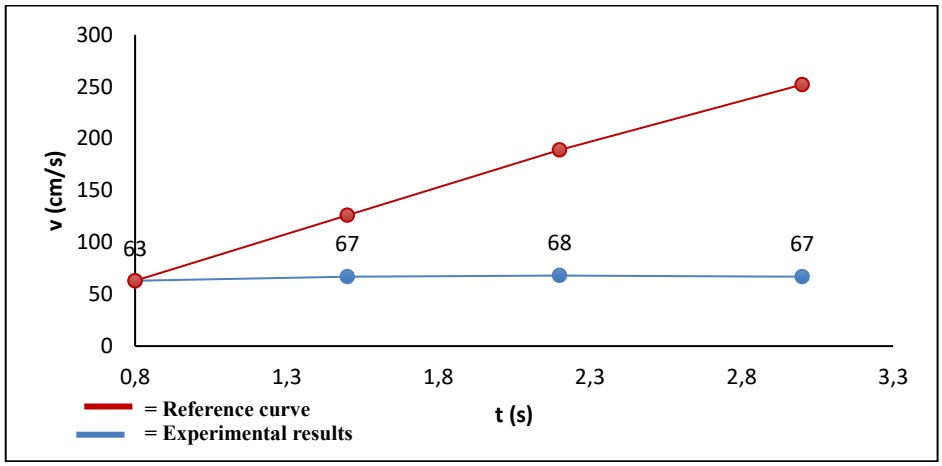

Figure 11. Comparison graph of v-t for an accelerated GLBB at an elevation angle of 10°

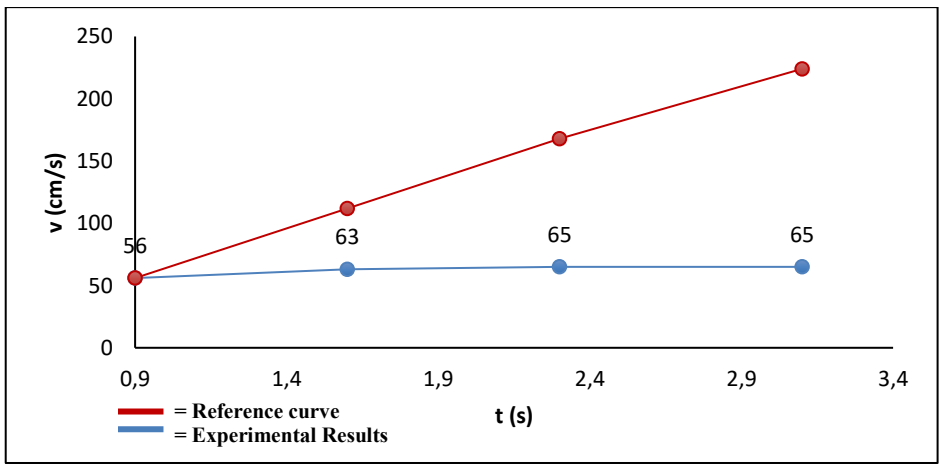

Figure 12. Comparison graph of v-t for an accelerated GLBB at an elevation angle of 7°

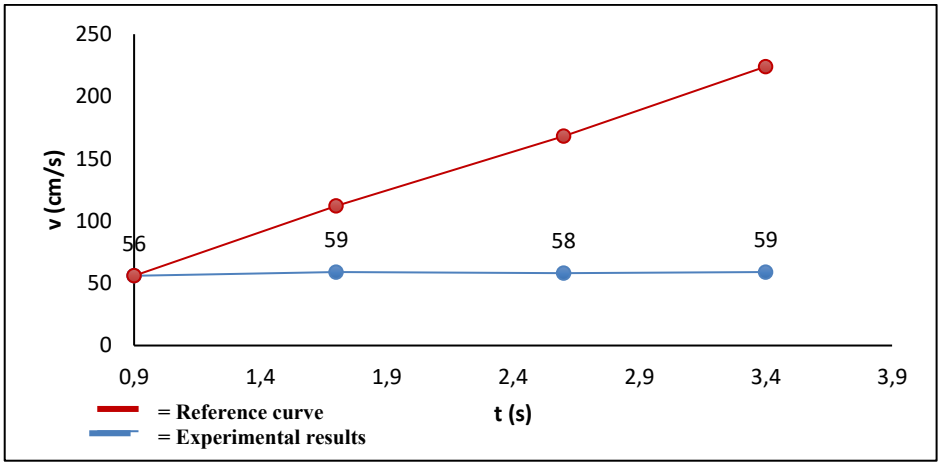

Figure 13. Comparison graph of v-t for an accelerated GLBB at an elevation angle of 4°

The results of the accelerated GLBB data, obtained using slope (elevation) angles of 13˚, 10˚, 7˚, and 4˚, show that the velocity values did not increase, and the experimental velocity-versus-time (v-t) graph is inversely proportional to the theoretical graph. This makes it impossible to determine the R^2 value, so the fit between the experimental v-t graph and the theoretical v-t graph falls into the "very poor fit" category. The experimental results are in stark contrast to the theory of uniformly accelerated linear motion (GLBB), which describes motion in a straight line with velocity increasing per unit of time; thus, the characteristic of GLBB is that the object's velocity changes over time, and in the case of accelerated motion, the object's velocity will increase (Nasution et al., 2025).

b. Decelerated GLBB

For the decelerated GLBB, line-follower robot experiments were conducted using angle variations of 10°, 7°, and 4°. At an angle of 13°, the robot experienced slippage (the wheels spun in place), so no experimental data could be obtained at this angle. In the decelerated GLBB test, the robot was able to move (climb) only at angles of 10°, 7°, and 4° so that data could be obtained for analysis. The test results are shown in the figure below.

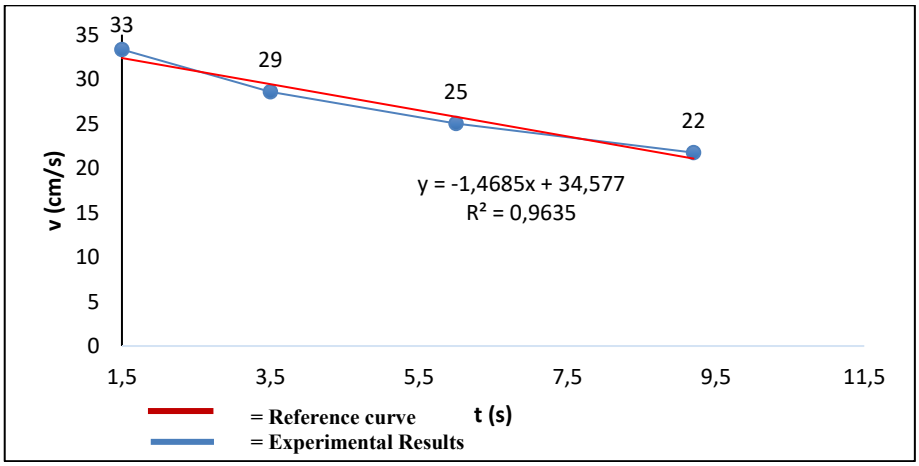

Figure 14. Comparison graph of v-t for the decelerated GLBB at an elevation angle of 10°

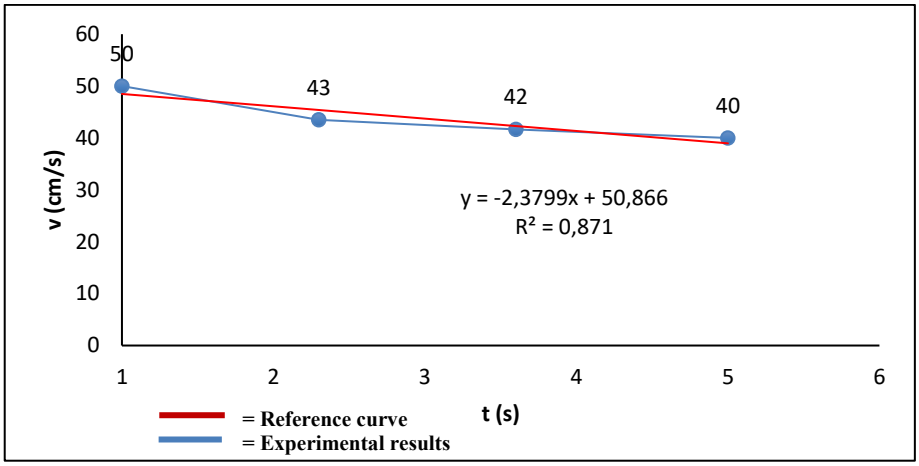

Figure 15. Comparison graph of v-t for a decelerated GLBB at an elevation angle of 7°

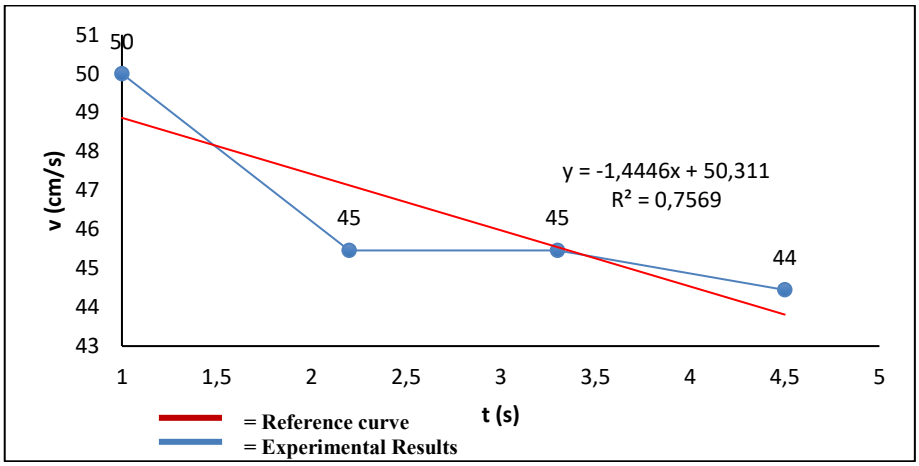

Figure 16. Comparison graph of v-t for the decelerated GLBB at an elevation angle of 4°

At an angle of 13˚, the robot experienced slippage (the wheels spun in place), so no experimental data could be obtained for analysis at this angle. At an angle of 10˚, the velocity-versus-time (v-t) graph showed a deceleration pattern that most closely matched the theory, with a regression value (the degree of fit between the theoretical and experimental graphs) of 0.9635. Furthermore, at an elevation angle of 7°, the robot decelerated, but the level of agreement with the theoretical graph was lower, with an R^2 value of 0.871. At an elevation angle of 4°, the robot still showed a tendency to decelerate but had the lowest R^2 value, namely 0.7569. At angles of 10°, 7°, and 4°, the results were inconsistent (unstable); the smaller the elevation angle, the more the data deviated from the linear curve. The average goodness-of-fit for the three elevation angles was 0.8618, which is categorized as "very good." The experimental results are consistent with the characteristics of decelerated GLBB, in that the object's speed gradually decreases over time and may even come to a stop (Fadilla et al., 2023). Based on the experimental results, it is concluded that the line-following robot can be used as a tool for decelerated GLBB experiments.

Test Results with a Standard Toy Car

Based on the accelerated uniform linear motion (GLBB) test results using the line-following robot, it was found that the velocity values and the velocity-versus-time (v-t) graph are inversely proportional to the concept of uniform accelerated linear motion (GLBB). Under these conditions, the robot did not experience an increase in velocity as expected, so the test results did not align with the characteristics of uniformly accelerated linear motion (GLBB).

A standard toy car was subjected to the same conditions as the line-following robot, namely a 2-meter-long track, varying elevation angles (13°, 10°, 7°, and 4°), and the same testing procedure.

This comparative test aims to determine whether the consistency of the experimental results is due to the characteristics of the line-following robot or to the track design and testing methods used. Thus, the test results for the toy car can serve as a reference for comparing the accelerated GLBB characteristics produced by the line-following robot. The test results are shown in the following figure.

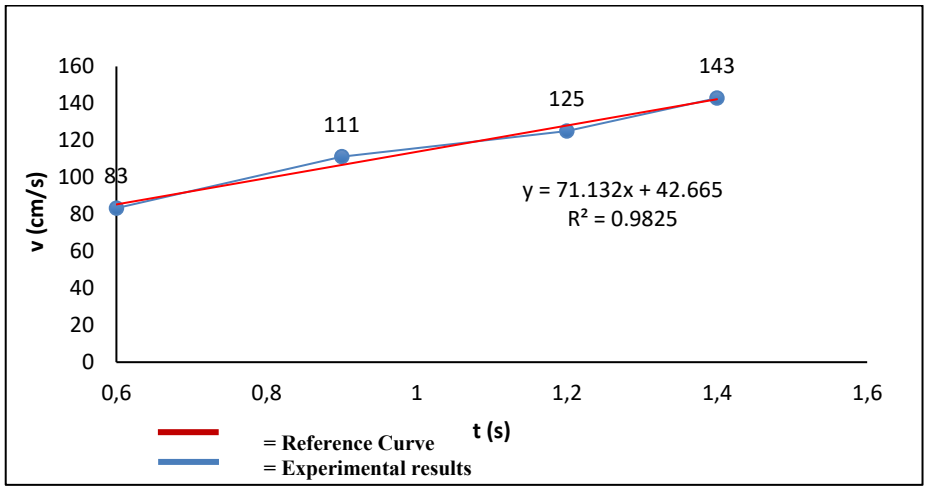

Figure 16. Comparison graph of v-t for accelerated GLBB at an elevation angle of 13°

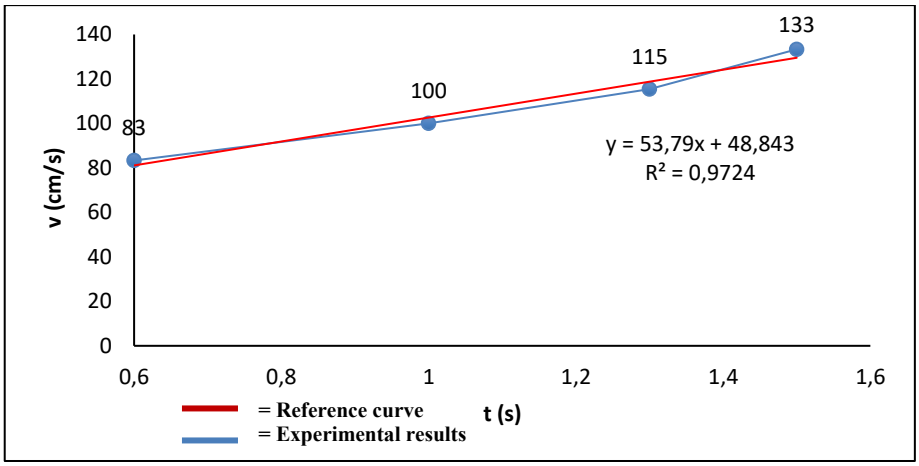

Figure 17. Comparison graph of v-t for an accelerated GLBB at an elevation angle of 10°

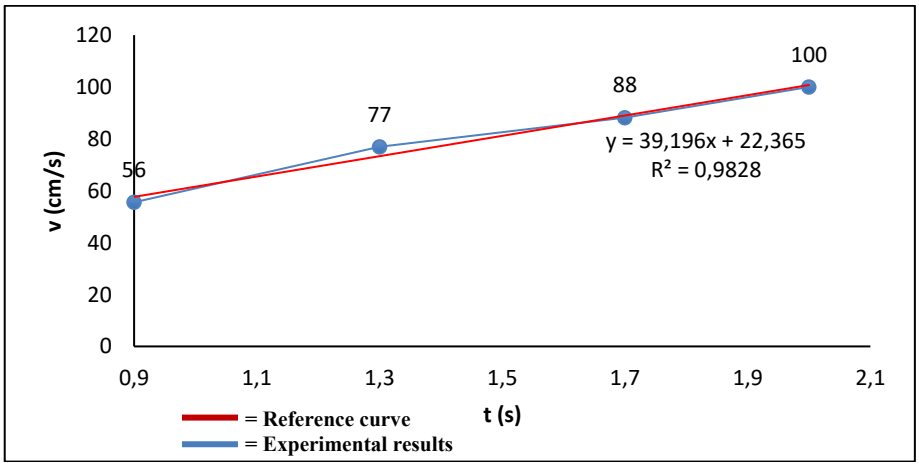

Figure 18. Comparison graph of v-t for an accelerated GLBB at an elevation angle of 7°

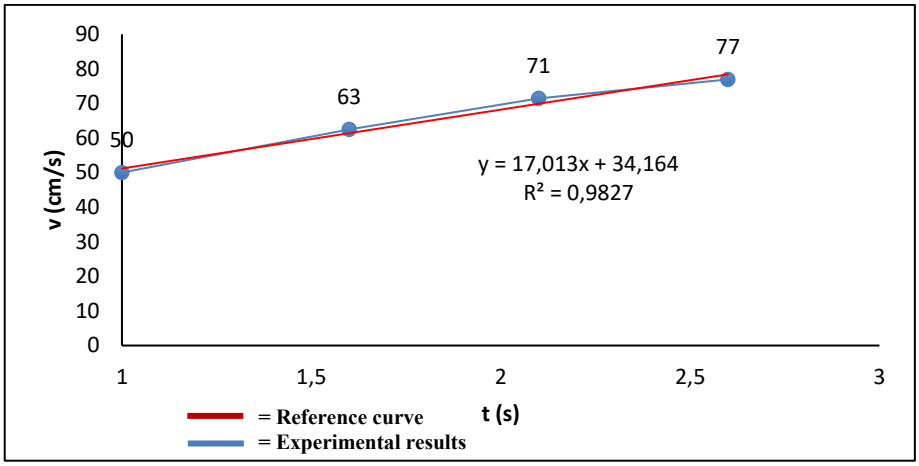

Figure 19. Comparison graph of v-t for an accelerated GLBB at an elevation angle of 4°

The experimental results at an angle of 13° show that the toy car's velocity increases as travel time increases, and the v-t graph exhibits a good fit with a regression coefficient of 0.9825. At an elevation angle of 10°, the toy car exhibits a gradual increase in velocity. A comparison of the v-t graphs yields a regression value (R^2) of 0.9724, indicating that the relationship between velocity and time still closely aligns with the theory of accelerated uniform linear motion. However, the acceleration is smaller compared to the 13° angle. At a 7° angle, the toy car's speed increased with a regression value of 0.9828. At a 4° angle, the car experienced an increase in speed as shown by the v-t graph; the comparison yielded a goodness-of-fit value of 0.9827, indicating that the experimental data still exhibits a very high level of agreement with the accelerated uniform linear motion (GLBB) theory. These results at elevation angles of 7° and 4° show that although the resulting acceleration is smaller at larger angles, the pattern of velocity increase is highly consistent with the concept of accelerated GLBB. From the four sets of robot motion data, the stability of the v-t graph fit is evident. With an average value of 0.9801, the fit is categorized as very good. The acceleration experienced by the toy car at angles of 13°, 10°, 7°, and 4° was 75 cm/s², 55 cm/s², 40 cm/s², and 27 cm/s², respectively. This is consistent with the principle that states that the greater the angle of elevation (incline) of an object, the greater its acceleration when moving uphill. Conversely, on a surface with a smaller angle of inclination, the object tends to move more slowly and may even come to a stop.

There are significant differences between toy cars and line-following robots. The toy car exhibits a consistent increase in speed on an accelerated GLBB, whereas the robot does not show a consistent increase in speed on the same track. This difference indicates that the discrepancy in the robot's experimental results on the accelerated GLBB is not caused by the track design or variations in the elevation angle, but is related to the technical characteristics and control system of the line-following robot.

Based on these conditions observed in the line-following robot, an analysis identified several main causes affecting its behavior, resulting in its speed remaining nearly constant with no increase, namely:

1. According to the physics of inclined planes: an object moving down an inclined plane experiences a component of the gravitational force parallel to the plane, given by$mg\sin\theta$. This force component tends to accelerate the object along the inclined plane. In a toy car, the wheels can move relatively freely, so the effect of the gravitational force along the plane is directly observable in changes in speed. This is demonstrated by the increase in the toy car's speed across all angle variations. Conversely, although the force of gravity also acts on a line-following robot, the robot's motion is influenced not only by gravity but also by the driving force of the motor (DC motor), the robot's mass, motor torque, power supply, and the control system (microcontroller). Therefore, the robot's motion response on an inclined plane differs from that of a toy car, whose wheels move relatively freely.

2. The DC motors connected to the wheel shafts are actively controlled: The line-following robot does not allow gravity to dictate its motion; the motor driver continuously supplies voltage according to the program so that motor speed is maintained both when going downhill and uphill.
3. The program uses speed control (PWM): generally, line-following robots are set to a fixed PWM (Pulse Width Modulation) value or even use PID. PID stands for proportional-integral-derivative, which is a system control method used to regulate a system's response to achieve a stable, fast, and accurate state (Erbay et al., 2024) . PID corrects the speed to keep it stable, so even if the path is uphill or downhill, the robot attempts to maintain its speed. Consequently, braking occurs when going downhill and slipping occurs when going uphill.

Another limitation of this study relates to the video-based measurement method using Tracker Physics. The accuracy of the measurement results depends on the quality and configuration of the video used in the analysis process. In this study, determining the ideal camera position was quite difficult because the entire 2-meter track had to remain visible throughout the recording process, especially when the track was set at various elevation angles. These conditions mean that the camera's position and angle of recording could potentially introduce perspective errors when determining the robot's travel time based on the video footage. In this study, several types of smartphone cameras were used to assess the stability and quality of the recorded video. Since this uncertainty has not been quantitatively evaluated in this study, the magnitude of measurement uncertainty stemming from the video recording configuration cannot yet be precisely determined. Therefore, this condition is one of the limitations directly stemming from the Tracker Physics software. Future research is recommended to use camera positions that are precise and aligned with the motion plane, as well as to consider the use of automatic timekeeping sensors with higher precision to minimize measurement uncertainty and improve the accuracy of the robot's travel time measurements.

This study shows that the use of line-following robots as physics experiment tools needs to be adapted to the motion characteristics being represented. Line-following robots can be used to help represent uniform linear motion (GLB) because they are capable of producing relatively constant speeds. Robots can also be used to demonstrate the tendency of uniformly accelerated linear motion (GLBB) to decelerate under certain conditions, particularly at angles of 10°, 7°, and 4°. However, the robot cannot yet be recommended for ideally representing uniformly accelerated linear motion (GLBB), as its motor and speed control systems tend to maintain the robot's speed, resulting in an acceleration pattern that does not align with theoretical characteristics. In an educational context, this study highlights the importance of validating robotics-based experimental tools before using them to represent physics concepts, so that the phenomena observed by students do not lead to inaccurate conceptual interpretations.

The limitations of this study include the characteristics of the DC motor and the robot's speed control system, the possibility of wheel slippage, and the uncertainty of the video-based measurement system using a physics tracker. Therefore, future research could develop a robot equipped with a larger DC motor and adjust the PWM control when the robot is descending an inclined plane. Additionally, an automatic timing sensor with higher precision could be considered to reduce measurement uncertainty. With these suggested improvements, the line-follower robot could serve as a more representative tool for experiments on linear motion. The experimental results show that the line-follower robot can be used in learning activities for uniform linear motion (GLB) and decelerated uniform linear motion (GLBB); however, for accelerated uniform linear motion (GLBB), the robot does not yet meet the criteria for use as a practical learning tool.

CONCLUSION

This study shows that line-following robots exhibit varying degrees of alignment in representing the concept of linear motion. In the GLB, the resulting v-t graphs fell into the "highly consistent" category with the theory, with an average R^2 value of 1. For decelerated GLBB, an average R^2 value of 0.8618 was obtained, falling into the "highly consistent" category at elevation angles of 10°, 7°, and 4°. Conversely, for accelerated GLBB, the line-following robot was unable to represent the theoretical characteristics because its speed tended to remain constant or even decrease across all elevation angle variations. The main contribution of this study is to provide empirical evidence regarding the capabilities and limitations of the line-following robot as a tool for straight-line motion

experiments: it is suitable for representing GLB and decelerated GLBB under certain conditions. However, it is not yet suitable for representing accelerated GLBB. These limitations are related to the characteristics of the DC motor and the robot's control system, wheel slippage, and the precision of time measurements. Therefore, future research is recommended to optimize the robot's drive and control systems by using high-torque DC motors so that the robot does not experience slippage (spinning in place) when traversing an incline. Furthermore, more effective and precise timing measurement tools should be employed, such as adding an automatic timing sensor to the robot, so that motion duration measurements are more accurate and facilitate experimental activities.

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