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Development of the Physics Practicum Apparatus based on Microcontroller: A Prototype Constructed from Misconceptions of Basic Kinematics Concepts

Endah Nur Syamsiah[1,a)], Muhammad Rizka Taufani[1,b)], Adam Hadiana Aminudin[1,c)], Rahadian Sri Pamungkas[2,d)], Reno Muhammad Fadilla[3,e)], Fatih Najah Nabilah[1,f)]

[1]*Universitas Kebangsaan Republik Indonesia, Jl. Terusan Halimun No.37, Lkr. Sel., Kec. Lengkong, Kota Bandung, Jawa Barat 40263, Indonesia*
[2]*Bandung Creative Society, l. Jalaprang No.4, Sukaluyu, Kec. Cibeunying Kaler, Kota Bandung, Jawa Barat 40123, Indonesia*
[3]*Kanazawa University, Kakumamachi, Kanazawa, Ishikawa 920-1192, Japan*

✉: [a)]endahnursyamsiah@gmail.com, [b)]mrtaufani29@gmail.com, [c)]adamhadianaa@gmail.com, [d)]rahadiansripamungkas@gmail.com, [e)]renofadilla01@stu.kanazawa-u.ac.jp, [f)]fatih.najah@gmail.com

Abstract

This research aims to develop a prototype of the P-PAM (Physics Practicum Apparatus based on Microcontroller), specifically designed to address misconceptions in basic kinematics. The method employed for the prototype development follows the ADPT model (Analysis, Design, Prototyping, and Testing). The misconceptions identified during the analysis process include: (1) If the object's position is in the positive coordinate, it indicates that the object is moving forward; (2) The acceleration of an object is proportional to its instantaneous velocity. The practicum apparatus designed to address Misconception 1 is intended to measure the distance of an object, with data processed using Arduino Uno and transmitted to a PC via Bluetooth. The distance data is then processed using Python to generate information regarding distance, velocity, and acceleration, which are displayed in graphs over time. The apparatus for addressing Misconception 2 presents initial and final velocity data, as well as the acceleration of an object rolling past two sensors. The prototype of the first practicum apparatus can generate real-time graphs of position versus time and speed versus time. The second apparatus prototype provides initial velocity, final velocity, and acceleration data. Additionally, the device can demonstrate uniform acceleration for different initial speeds, as the incline is kept constant. There are 7 out of 10 acceleration data that fall within the confidence interval $CI = [1,47763; 1,53197]$ at the 96% confidence level. The prototype we created can present scientific facts from two misconceptions in basic kinematics material, in addition, our prototype can be used in learning that focuses on conceptual change.

Keywords: prototype, misconceptions, basic kinematics, graph, P-PAM

INTRODUCTION

Kinematics is a branch of mechanics that studies the motion of objects or systems of objects without considering the cause. Kinematics focuses on position, velocity, and acceleration. Understanding kinematics is needed before studying more complex topics, such as dynamics functional in everyday life and technological development (Molotnikov and Molotnikova, 2022; Cashman and O'Mahony, 2022).

The construction or formation of scientifically accurate conceptual understanding related to the concept of kinematics during the learning process is greatly influenced by students' initial conceptions. If their initial conceptions are in line with new knowledge, then an assimilation process occurs that strengthens previous understanding. Conversely, if students have misconceptions, this will hinder the construction of accurate physics concepts. Misconceptions tend to reject new, more scientific ideas (Admoko, 2023; Setyarini & Admoko, 2021; Nasution et al., 2021; Vosniadou, 2020; Syamsiah et al., 2019; Samsudin et al., 2023; Sundagara et al., 2021; Rusilowati et al., 2020; Suhandi et al., 2020).

Misconceptions are often found in kinematics material where students believe that in position-time and velocity-time graphs, positive areas indicate objects moving forward, among other misconceptions (Timothy et al., 2023; Suárez, 2023; Admoko, 2023; Handika et al., 2019). These misconceptions are inconsistent with scientific facts and can hinder a deeper understanding of physics concepts.

Reconstruction or revision of these misconceptions is important to ensure that students understand physics concepts scientifically (Samsudin et al., 2021; Lin et al., 2023; Sari et al., 2021). One effort that can be made is to develop learning media that present scientific facts related to physics concepts. These facts are expected to cause cognitive conflict in students so that students' misconceptions can be overcome (Putri et al., 2022; Wibowo et al., 2017; Anggoro et al., 2019; Resbianto, 2022).

Previous researchers such as Wibowo et al. (2017) & Fongsamut et al. (2022) conducted a reconstruction of the concept of kinematics material using simulation as the primary approach to help students' understanding of kinematics concepts. Simulation of understanding kinematics material can be realized through the use of augmented reality-based textbooks, which present 3D animations and interactive videos to help students understand abstract concepts more realistically and interestingly (Bakri et al., 2023; Johan et al., 2023). This is supported by data analysis using the VOSviewer application on 500 journal titles downloaded from the Google Scholar database, using the keywords "misconception," "physics," and "kinematics". FIGURE 1 reveals that research on kinematics misconceptions, particularly in graph construction, rarely focuses on developing physical practicum apparatuses. Most research relies on computer simulations. This is shown in FIGURE 1, it can be seen in the zoomed image results on the left of the image there is a line connecting the kinematics material and the graph connected to the computer. Meanwhile, the right of FIGURE 1 shows the line of connection between the kinematics graph and simulation. There is no connection between kinematics and the making of practical tools.

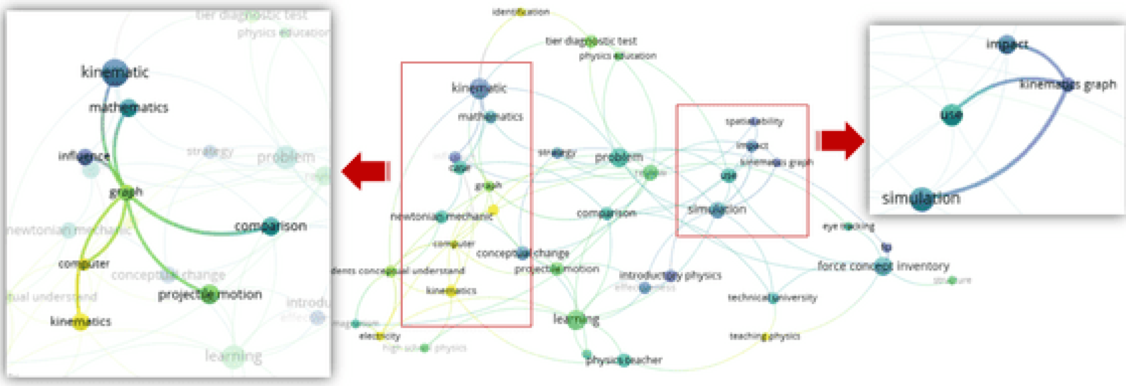


FIGURE 1. Analysis of research trends in Basic Kinematics using VOS Viewer

The lack of use of practical tools in kinematics material to reconstruct misconceptions is the main focus of this article. This is because, in kinematics material, it is possible to make practical tools that can further hone students' practical skills. Practical work has been proven to improve student learning outcomes by providing direct experience relevant to real phenomena. Good laboratory management and adequate facilities are essential to support practical learning activities (Damayanti & Sinuraya, 2023; Suseno et al., 2021). Practical activities supported by teaching aids can also provide simulations that connect theory with real-world applications, making physics learning more relevant and engaging for students (Asrowi et al., 2023).

Today's technological developments can support practical activities because technology enables more sophisticated system integration, such as real-time measurement, automatic analysis, and precise control. A microcontroller is one of the technologies that can be used to support practical tools to remediate misconceptions and reconstruct concepts in kinematics material. Microcontrollers provide good processing capabilities, flexibility for reprogramming to suit experimental needs, ease of hardware control, user-friendly interfaces for sensors and actuators, and lower costs compared to other control solutions, enabling the development of effective, efficient, and economical experimental tools (Doyan et al., 2023; Ďuriš et al., 2023; Huda et al., 2023; Candraditya et al., 2024).

Therefore, this research aims to develop educational media as a practicum apparatus based on misconceptions identified in Basic Kinematics concepts, utilizing a microcontroller-based system referred to in this study as the Microcontroller Based Physics Practicum Apparatus (P-PAM).

METHODS

This study employs the ADPT method, which consists of four stages: Analysis, Design, Prototyping, and Testing. This method is adapted from the widely-used ADDIE framework (Analysis, Design, Development, Implementation, and Evaluation) by incorporating a prototyping approach. The ADDIE method is commonly applied in educational media development, offering a systematic framework for designing, developing, and evaluating learning processes (Darman et al., 2023; Kurniawan et al., 2023; Sulsilah et al., 2022; Baifeto et al., 2022). On the other hand, the Prototyping method is often used in software and system development, application design, and research that involves iterative product design and testing. Prototyping enables developers to create an initial version (prototype) that can be tested and gradually refined (Camburn et al., 2017; Kondafeti et al., 2021).

The integration of these two methods into the ADPT approach allows for the combination of educational media development and technological advancement, leveraging the strengths of both methods. In ADPT, the Development phase in ADDIE is replaced with Prototyping, as it allows instructors and developers to make iterative improvements to the product before reaching the final version. This process enables repeated refinement of the prototype to ensure it meets the identified needs. In addition, the product produced at this stage is a prototype of P-PAM.

The implementation and evaluation stages were replaced with the testing stage because the research conducted had not yet entered the stage of implementing the practical tools to students (respondents) and evaluating the influence of the tools made on the reconstruction of misconceptions in the concept of kinematics. Thus, the final stage of making this practical tool is the stage of testing the tool or testing the functionality of the tool. The stages of the ADPT method used in this research are illustrated in FIGURE 2.

Analysis

The analysis stage involves a needs assessment. This phase begins by identifying misconceptions as the primary issue in understanding the Basic Kinematics concept. Subsequently, scientific conceptions related to Basic Kinematics are identified to determine appropriate solutions. The following are the results obtained in TABLE 1.

Design

In the design phase, a comprehensive design of both the practical activities and the apparatus used for the experiments is undertaken. The primary focus of the design process is to ensure that the activities and tools developed can effectively present the scientific concept of Basic Kinematics and confront the misconceptions held by students.

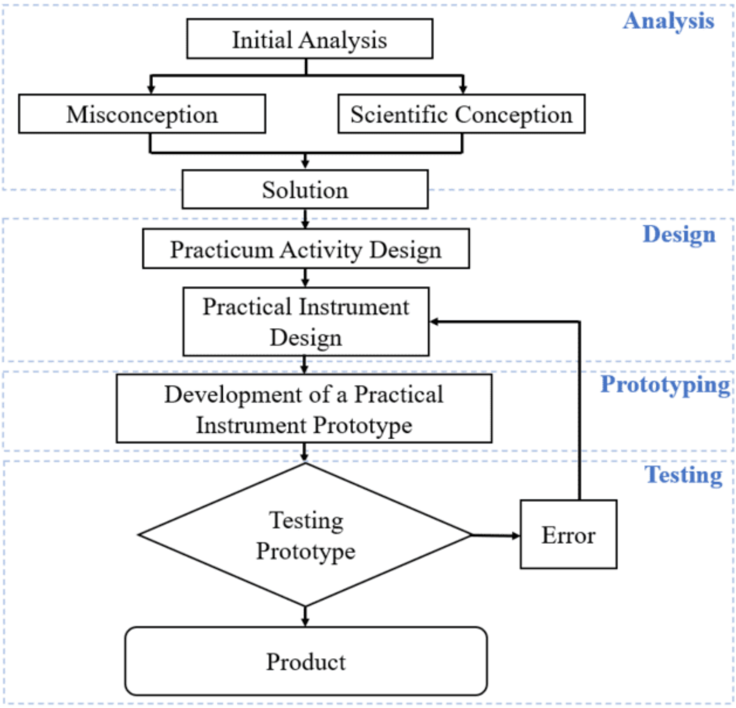


FIGURE 2. Flowchart of ADPT research model

TABLE 1. Misconceptions and scientific conceptions related to the principles of Basic Kinematics

No.	Misconceptions	Scientific Conceptions
1.	As long as the object's position remains in the positive coordinates, it indicates that the object is moving forward.	• The position of the object on the S-axis remaining constant over time indicates that the object is at rest. • The displacement of the object on the S-axis from a larger value to a smaller value indicates that the object is moving backward, even while still within the positive region of the S-axis.
2.	The acceleration of an object is proportional to its speed.	Acceleration alters velocity every second. If the final velocities of all three are equal over the same time interval, the car with the smaller initial velocity experiences the greatest change in velocity.

Design of Activities and Practicum Apparatus for Misconception 1

The first misconception pertains to the inconsistency between the understanding of reading movement graphs of objects and the actual scientific principles. To address this misconception, a practical apparatus is required that can analyze the motion of objects and display their movement graphs in real-time. The object being recorded must be capable of moving uniformly in a straight line, either forward or backward, with movement controlled via a remote control.

The motion of the object, regulated by the remote control, will be analyzed by a motion sensor. The sensor measurements will be processed using Arduino, which will subsequently transfer the data via Bluetooth to a PC for graphical representation. An illustration of the operational flow chart is presented in FIGURE 3.

The sensor measures the distance, which is subsequently converted into the average speed (s) for each time interval (Δt). The conversion of distance data is achieved by calculating the difference between the current distance measurement dn and the previous distance measurement (d_{n-1}), then dividing this difference by the time interval between the two measurements, in accordance with the Equation (1).

$$s = \frac{d_n - d_{n-1}}{\Delta t} \quad (1)$$

The distance data (d) and speed (s) are transmitted via Bluetooth to the PC, where the data is then processed to generate graphs using Python programming language.

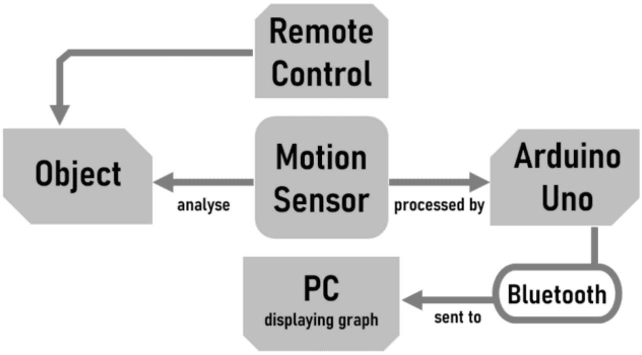


FIGURE 3. Flowchart of the operational system of the P-PAM 1 prototype

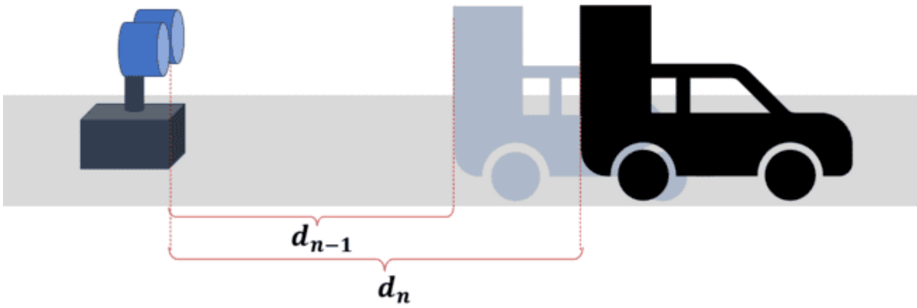
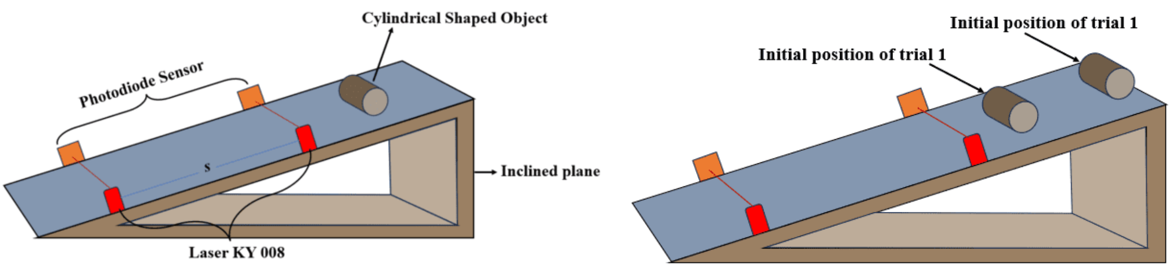


FIGURE 4. Design of the P-PAM 1 prototype apparatus

Design of Activities and Practicum Apparatus for Misconception 2

The second misconception pertains to the understanding of speed (s) and acceleration (a). The designed practical activity involves moving an object on an inclined plane with a constant angle of inclination and initial speed $(s = 0)$. The starting point can be adjusted at least twice to demonstrate the differences in speed at the same observation point, while the acceleration (a) remains constant due to the unchanging angle of the inclined plane. The design of the practical apparatus and the experimental setup is illustrated in FIGURE 5(b).

Two photodiode sensors are positioned at two different points and illuminated by lasers directed precisely at each photodiode. The lasers are arranged in such a way that their beams directly strike the photodiodes.



(a) (b)

FIGURE 5. (a) design of the practical apparatus; (b) experimental design

The object utilized is a solid homogeneous cylinder with mass (m) and radius (r), whose moment of inertia satisfies $I = \frac{1}{2}mr^2$. The selection of the rolling object is intended to eliminate the unknown variable of the coefficient of friction between the surface of the cylinder and the track. FIGURE 6 illustrates the derivation of the expression for the acceleration of the center of mass of the solid cylinder.

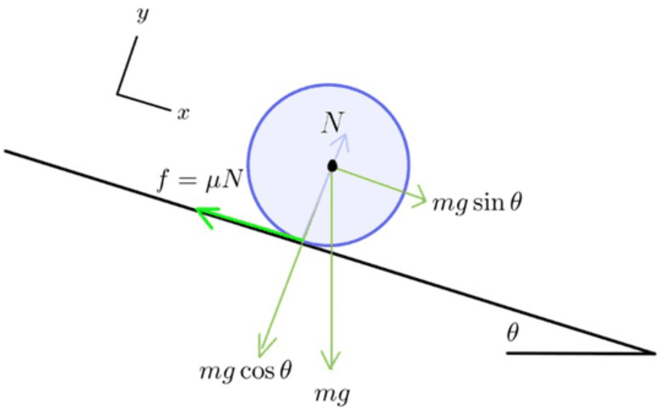


FIGURE 6. Force diagram

From the force diagram of FIGURE 6, the equations of motion for the x-axis and y-axis are obtained in Equation (2) and (3).

$$\Sigma F_x = mg \sin\theta - f = m\, a_{pm} \tag{2}$$

$$\Sigma F_y = N - mg \cos\theta = 0 \tag{3}$$

where $N, \theta, f, g,$ and a_{pm} represent the contact force exerted by the inclined plane, the angle of inclination of the plane, the frictional force from the inclined surface, the acceleration due to gravity, and the acceleration of the center of mass of the cylinder along the x-axis, respectively. In this case, the solid cylinder rolls with the rotational motion equation in Equation (4).

$$\Sigma\tau = fr = I\alpha \tag{4}$$

where α denotes the value of the angular acceleration of the solid cylinder. To determine the acceleration of the center of mass of the cylinder, this experiment assumes perfect rolling $a_{pm} = \alpha r$. Thus, from Equations (2) and (4), the result obtained is Equation (7).

$$m\, a_{pm} = mg \sin\theta - \frac{I\alpha}{r} \tag{5}$$

$$\frac{3}{2} m\, a_{pm} = mg \sin\theta \tag{6}$$

$$a_{pm} = \frac{2}{3} g \sin\theta \tag{7}$$

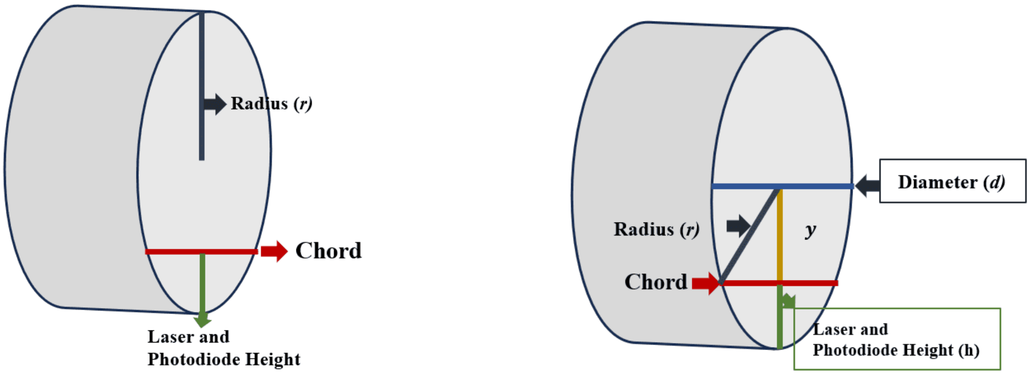
Equation (7) represents the expression for the acceleration of the center of mass of the solid cylinder used in the experiment. The determination of speed (s) and acceleration (a) begins with the measurement of the arc length of the cylinder used for the practicum. The arc length can be determined using Equation (8) based on Figure 7.

$$chord = \sqrt{r^2 - (r-h)^2} \times 2 \tag{8}$$

The speed (s) and acceleration (a) of the object are calculated when the cylindrical object obstructs the laser beam directed at the photodiode. The time (t) during which the object blocks the laser beam towards the photodiode represents the duration required for the object to travel the length of the chord.

Using the data for time (t) and the length of the chord, the speed (s) of the object as it passes each sensor can be determined using the Equation (9).

$$s = \frac{chord}{t} \tag{9}$$



(a) (b)

FIGURE 7. Determination of the chord length

The rolling object will pass through two photodiode sensors, allowing for the acquisition of two velocity values at different points. When the time taken for the object to travel the distance between the sensor placements is known, the acceleration of the center of mass of the object can be calculated. The procedure involves subtracting the velocity measured at the second sensor (s_2) from the velocity measured at the first sensor (s_1), and then dividing by the time taken for the object to travel from the first sensor to the second (Δt). Mathematically, this is expressed by Equation (10).

$$a_{pm} = \frac{s_2 - s_1}{\Delta t} \tag{10}$$

Prototyping

In the prototyping phase, the process begins with the identification of the main components to be utilized. This selection is made based on the functions and requirements of the designed apparatus. Once all components are identified, the next step involves assembling the prototype of the practical apparatus.

Testing

The testing phase is conducted to evaluate the performance of the developed prototype of the practical apparatus, ensuring its capability to concretely present the scientific concepts related to Basic Kinematics. The indicators of success for the activities and apparatus developed are outlined in the TABLE 2.

TABLE 2. Indicators of Success for the Apparatus

Misconception	Indicators of success for the apparatus
1	The system is capable of generating real-time graphs of position *d* and speed *s* as functions of time.
2	• The system can determine the speed *s* at two different sensor points and calculate the acceleration *a*. • The system can present an acceleration *a* of equal magnitude for two experiments with different initial speeds s_0.

The second indicator of success, in addition to evaluating the functionality of the prototype, is to test the level of accuracy of the tool in measuring the acceleration of objects on the same plane slope. The data used in this process is acceleration data obtained with the level of inclination of the inclined plane kept constant so that the resulting acceleration is the same size. This test is carried out using standard deviation analysis to ensure measurement accuracy.

$$SD = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \tag{11}$$

where (SD) is the measurement uncertainty (standard deviation), n is the amount of data and x is the acceleration data obtained in the experiment and $\bar{x}$ is the average of the acceleration data.

The results of the uncertainty are then used to determine the percentage of relative error with the Equation (12).

$$relative\ error\ (\in) = \frac{SD}{\bar{x}} \times 100\% \tag{12}$$

in addition to standard deviation and relative uncertainty, the confidence interval of acceleration data is sought through Equation (13).

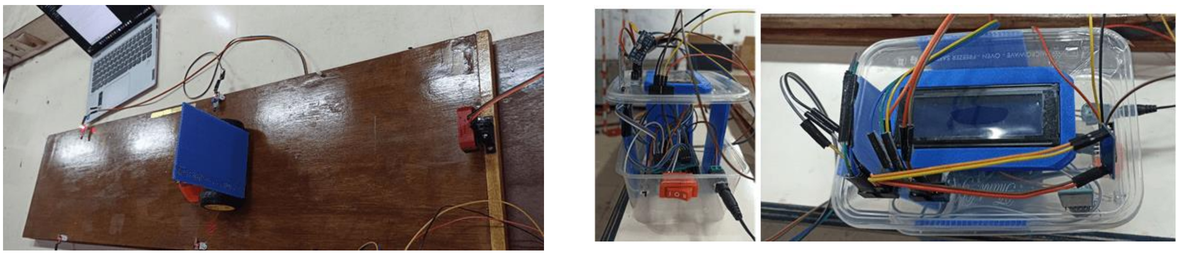
$$CI = \bar{x} \pm t_{df,\alpha} \frac{SD}{\sqrt{n}} \tag{13}$$

RESULTS AND DISCUSSION

The results of this study include prototypes and the results of the prototype testing. The prototype that was successfully developed is a tool that can be used for two different experiments. The following is a prototype that was successfully created in this study.

Components and assembly of the apparatus for Misconception 1

The core hardware components of the apparatus used are: (1) Arduino Uno R3; (2) Bluetooth HC-05; (3) Ultrasonic sensor HC-SR04; (4) remote-controlled mobile robot; and (5) laptop. The software utilized for coding includes Arduino IDE, which uses C++ language, and (2) Python 3.12. FIGURE 8 illustrates prototype of the apparatus for Misconception 1 that has been assembled.



(a) (b)

FIGURE 8. (a) the track board that has been installed with the ultrasonic sensor; (b) the embedded system circuit of Arduino, LCD, Bluetooth, and switch

The ultrasonic sensor is mounted on a wooden track board. The remote-controlled car used is equipped with a small blue infrared board, as shown in FIGURE 8a, serving as a medium for reflecting the ultrasonic waves emitted by the sensor. The embedded system in FIGURE 8b represents a combined embedded system of practicum 1 and 2. Thus, a switch is installed in the circuit to switch between different types of experiments.

Components and assembly of the apparatus for Misconception 2

The hardware components used include: (1) Arduino Uno R3; (2) photodiode sensor (receiver); (3) KY-008 laser; and (4) a cylindrical object. The software utilized for coding is Arduino IDE, which employs C++ language. FIGURE 9 is a photo of the assembled practicum prototype for misconception 2.

FIGURE 9. The diagram illustrates the track and the positioning of the sensors on the practicum apparatus 2

The installation of the photodiode sensor is carried out by first positioning the KY-008 laser as a reference. Using a level and ruler, the position of the photodiode can be determined accurately. The edge of the track is equipped with a hinge, allowing the practitioner to adjust the angle of the inclined plane. Additionally, the hinge also enables the board to be flattened for use in practicum 1.

The success indicator for the apparatus developed to address the first misconception is that the system can generate real-time graphs of position (d) and speed (s) against time. Based on the experiments conducted, this apparatus has met its success criteria. The results produced by the system can be observed in FIGURE 10.

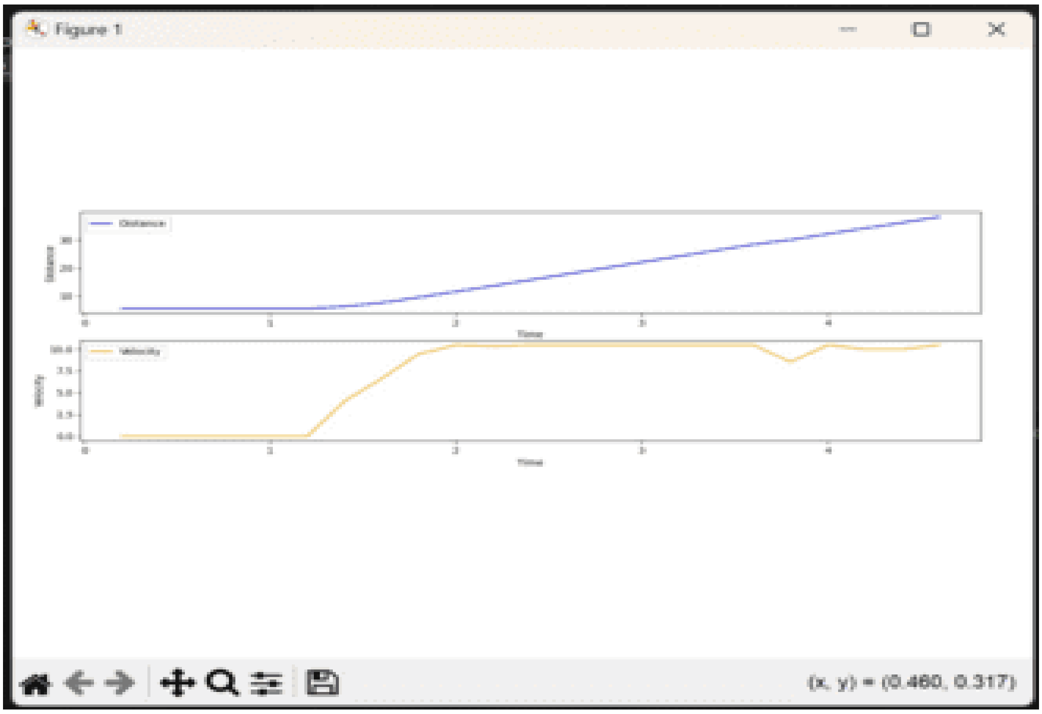
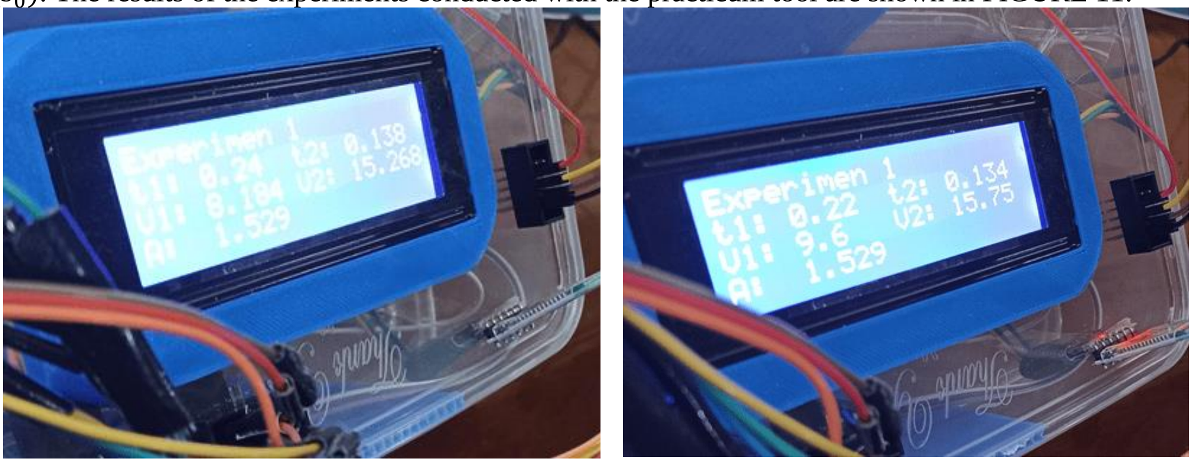


FIGURE 10. Results of the graph from Practicum Tool 1

The designed practicum tool is capable of presenting graphs of position versus time and speed versus time in real time. Given that the issue of misconceptions centers on the interpretation of graphs that do not align with scientific facts, the real-time generation of these graphs adequately fulfills the established indicators.

The indicators of success for the development of the tool addressing the second misconception are: (1) the system can determine speed (s) at two different sensor points and calculate its acceleration (a); (2) the system can present the same acceleration (a) for two experiments with different initial speeds (s_0). The results of the experiments conducted with the practicum tool are shown in FIGURE 11.



(a) (b)

FIGURE 11. (a) photo of the results from the first experiment, (b) photo of the results from the second experiment with a different initial speed compared to the first

The results of the tool testing carried out can be seen in the TABLE 3.

TABLE 3. second misconception experiment data

Experiment	(s)	(s)	Initial speed (s_0) (cm/s)	Final speed (s_t) (cm/s)	Acceleration (a) (cm/s^2)	SD
1.	0.24	0.14	8.1840	14.900	1.529	0.035826
2.	0.22	0.13	9.6000	15.748	1.529	
3.	0.20	0.13	10.605	15.977	1.460	
4.	0.25	0.14	8.4840	14.999	1.500	
5.	0.18	0.12	11.783	17.084	1.550	
6.	0.20	0.13	10.605	16.136	1.440	
7.	0.20	0.13	10.605	16.293	1.480	
8.	0.21	0.13	10.100	15.969	1.500	
9.	0.22	0.13	9.6410	15.812	1.540	
10.	0.20	0.13	10.605	16.356	1.520	

The results of data processing in SPSS to determine the Confidence Interval can be seen in the TABLE 4.

TABLE 4. Results of One-Sample Test data analysis in the SPSS program

One-Sample Statistics				
	N	Mean	Std. Deviation	Std. Error Mean
VAR00001	10	1.50480	.035826	.011329

One-Sample Test (Test Value = 0)						
					96% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
VAR00001	132.825	9	.000	1.504800	1.47763	1.53197

TABLE 3 shows the standard deviation results obtained is 0.035826. The Confidence Interval in TABLE 4 obtained with a 96% confidence level is $CI = [1.47763; 1.53197]$, which can be interpreted as data that is in the CI range is data with a confidence level of 96%. 7 data out of 10 or 70% of the experimental data that we obtained fell into the confidence interval.

The graph obtained from the experiment (in FIGURE 10) is not perfect because the movement of the object used is not at a constant speed; sometimes, the speed of the object decreases because the object turns slightly. This disturbance can actually be overcome if a separate straight track is made whose sides have walls that can direct the movement of the object to be straight. As Ali (2020) did in his research, for the motion practicum tool, a trajectory was designed that allows objects to move in a straight line. Because the ESP is already integrated with Bluetooth and Wifi, if you use Arduino, you have to create your own code to connect to Bluetooth first. This can lighten the system's workload (Mane, 2021; Rak, 2021).

The acceleration obtained in the second experiment was quite varied, although the acceleration value should be the same for the same level of track slope, although the difference is not too significant. There are two pairs of data that really meet the needs, namely data pairs 1 and 2 and also data pairs 4 and 8. Data 1 and 2 produce the same acceleration, namely 1.529 cm/s^2, while data pairs 4 and 8 produce an acceleration of 1.500 cm/s^2. These two pairs of data are scientific facts that we want to show, even with different initial and final velocities of the same cylinder as long as the object is on an inclined plane with the same angle, the acceleration of the object is the same. If there are other researchers who are interested in developing this tool, it is recommended to replace the type of sensor used or replace the rolling motion with a free fall motion, because the object may hit the sensor.

When an object hits the sensor during the rolling process, this can cause a mismatch between the laser and the photodiode, loose cables, and affect the accuracy of the results. In addition, vibrations on the track when the object rolls can also reduce the accuracy of the sensor.

Overall, based on the success indicators set at the beginning, the prototype created successfully met all of these indicators. Thus, this prototype can be used as a learning tool in the classroom, especially to help teachers or lecturers in presenting scientific facts to overcome misconceptions: (1) As long as the object's position remains in the positive coordinates, it indicates that the object is moving forward. because this prototype successfully displays $(s - t)$ and $(v - t)$ graphs of object movement in real time; (2) The acceleration of an object is proportional to its speed. The prototype can show different initial and final velocity values in two experiments but produce the same acceleration value.

The use of this prototype can be combined with models or approaches that focus on conceptual change. The presentation of scientific facts is part of the stage of conceptual change, which is carried out after the confrontation stage of students (Samsudin et al., 2021; Suhandi et al., 2020; Suárez et al., 2023).

CONCLUSION

This study successfully developed a prototype of the Physics Practicum Apparatus based on Microcontroller (P-PAM) specifically designed to address misconceptions in the concept of Basic Kinematics. Misconception 1 pertains to the understanding that when the object's position is at a positive coordinate, it indicates that the object is moving forward. Misconception 2 relates to the notion that an object's acceleration is proportional to its instantaneous speed. The practicum apparatus designed to address Misconception 1 measures the distance of an object, with data processed using an Arduino Uno and transmitted to a PC via Bluetooth. The obtained distance data is then processed using Python to generate information regarding distance, speed, and acceleration, which will be displayed in respective graphs over time. The practicum apparatus addressing the second misconception presents data on initial and final speeds, as well as the acceleration of the rolling object as it passes through two sensors. The prototype of the first practicum apparatus is capable of providing real-time graphs of position versus time and speed versus time. The prototype of the second practicum apparatus can present initial speed, final speed, and acceleration of the object. Moreover, this apparatus can produce consistent acceleration information for varying initial speeds, as the inclination level is maintained constant. This prototype has been able to meet all the indicators of the tool's functionality that have been determined, so this tool can be used in learning, especially those that focus on the conceptual change approach. However, this prototype has not been implemented for students, so the effectiveness of using the prototype for the remediation of misconceptions or construction of concepts in basic kinematics is not yet known. Further researchers can use this prototype for this purpose. In addition, this tool can be developed better by replacing the components used, such as replacing the Arduino microcontroller with ESP, and creating a special path for objects to move straight.

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