Research Article

Investigating Wireless Sensor Kit for Horizontal Circular Motion Analysis

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ABSTRACT

Circular motion is a challenging topic in physics education, primarily due to the multiple quantities involved, such as linear and angular quantities, as well as Newton's laws of motion. This often leads to confusion among students. In this study, we developed an experimental device for uniform circular motion using an ESP8266 microcontroller, an IR sensor, an accelerometer, and a gyroscope sensor. The device consists of a microcontroller, sensors, battery, and metal block, which are connected to a circular plate. The device wirelessly transmits data to a preferred display device. We investigated the relationship between centripetal acceleration, angular velocity, and the radius of motion. The results revealed a direct variation between centripetal acceleration and both angular velocity and moving radius, consistent with the centripetal acceleration equation. Additionally, this device is cost-effective and provides students with real-time physical data on circular motion, making it a valuable tool for classroom use, thereby enhancing students' educational experience.

Keywords: Circular Motion, ESP8266, Gyroscope, Accelerometer, Centripetal Acceleration

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Introduction

Circular motion is a fundamental topic covered in physics education at Thai high schools. However, the traditional experimental apparatus used for circular motion experiments is prone to significant human error since it relies on manual observation, timekeeping, and note-taking. To address this issue, researchers have explored various electronic devices as measurement tools to minimize human error in circular motion experiments.

For instance, Hochberg et al. [1] employed smartphone sensors, Azizahwati et al. [2] utilized an Arduino Uno with a photodiode sensor, and other researchers [3-5] have explored the compatibility of microcontrollers with different sensors. These studies have demonstrated the effectiveness of using electronic devices to study circular motion with reduced human error. However, it should be noted that some experimental setups are limited in terms of their ability to collect real-time data and simultaneously store data logs.

In this research, a novel approach was developed for horizontal circular motion experiments by employing the ESP8266 microcontroller. This microcontroller was paired with an IR sensor, a gyroscope, and an accelerometer sensor. The data collected by the sensor kit can be transmitted wirelessly via Wi-Fi to a designated display device. This enables the real-time reading of experimental data while simultaneously storing data logs. As a result, researchers can access and analyze the experimental data in real time, while also having the ability to review and analyze data logs at a later stage.

This integrated system enhances the efficiency and accuracy of data collection in horizontal circular motion experiments, overcoming the limitations of traditional methods. It provides researchers and students with a comprehensive and flexible approach to studying circular motion, offering both real-time data analysis and the ability to review experimental data logs for further investigation and analysis.

Theoretical Background

The motion exhibited in Figure 1, depicting horizontal circular motion, can be accurately described using Newton's laws of motion:

$$\sum \vec{F}_c = m\vec{a}_c \quad (1)$$

Where $\sum \vec{F}_c$ is the centripetal force of circular motion, m is the mass, and $\vec{a}_c$ is the centripetal acceleration of circular motion.

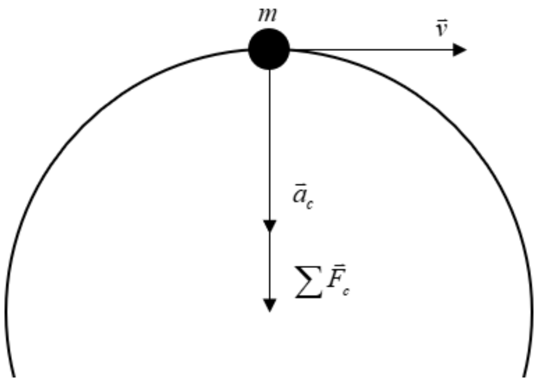

Figure 1 Force, acceleration, and velocity of an object in horizontal circular motion.

The centripetal force associated with circular motion exhibits a connection with various other quantities pertaining to circular motion. When considering only the magnitude, a relationship can be established as follows:

$$a_c = \omega^2 r \tag{2}$$

$$a_c = \left(\frac{2\pi}{T}\right)^2 r \tag{3}$$

Where ω represents the angular velocity of the circular motion, r denotes the radius of the circular motion, and T signifies the period of the circular motion.

The gyroscope-accelerometer sensor operates based on the principles of acceleration and angular velocity measurement. An accelerometer is responsible for detecting acceleration or changes in velocity. It can sense movement or tilt in three dimensions: X, Y, and Z axes. The accelerometer comprises a mass suspended by springs, which generate a small electrical current proportional to the applied acceleration. When the accelerometer experiences movement, the mass moves, causing a change in the electrical current. By measuring these changes, the device can determine the acceleration or tilt in the corresponding direction. In a stationary state, the accelerometer readings in most axes will be close to zero. However, the z-axis, aligned with gravitational acceleration, will have a reading near 9.81 m/s^2, as shown in Figure 2. On the other hand, a gyroscope measures angular velocity or rotational changes. It detects rotational movement around three axes: pitch, roll, and yaw. A typical gyroscope incorporates a spinning rotor, and its orientation remains fixed due to the principle of angular momentum. When the gyroscope rotates, it experiences a force that attempts to change its orientation. Sensors, such as piezoelectric elements or vibrating structures, detect this force and convert it into electrical signals. By analyzing these signals, the device can determine the rate and direction of rotation. When the gyroscope is in a stationary state, the rate of angle change or angular velocity measured on all three axes is zero.

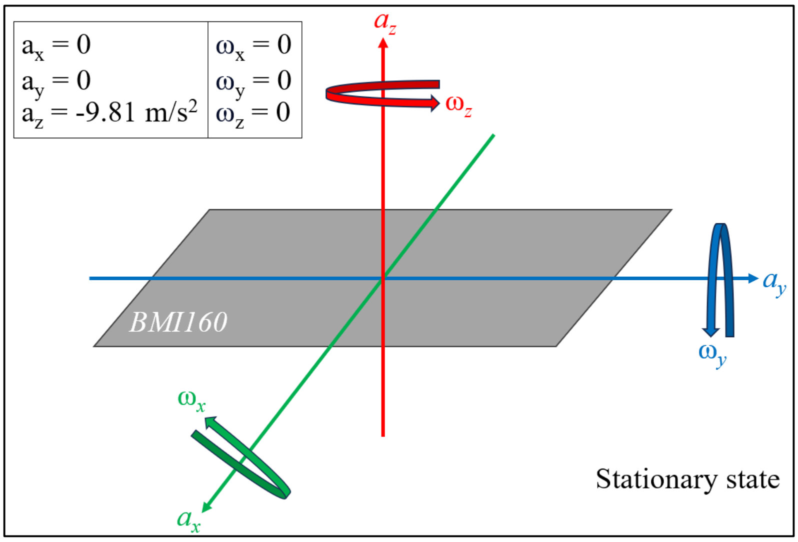

Figure 2 Angular velocity and centripetal acceleration readings from the gyroscope-accelerometer sensor (BMI160) in a stationary state.

In this study, horizontal circular motion was simulated by employing an electric turntable. This experimental setup ensured that the angular velocity remained constant or experienced minimal changes throughout the duration of the experiment.

Experimental Setup

The first step of the experimental setup involved assembling the microcontroller, such as the ESP8266 or ESP-32, along with various sensors, including a gyroscope, accelerometer, and IR sensor, as illustrated in Figure 3. Subsequently, the sensor set was installed onto the electric turntable, as shown in Figure 4. The next step involved programming the ESP8266 to work in conjunction with the gyroscope and accelerometer. Once the program is completed, the device should be capable of reading angular velocity and centripetal acceleration. These data will be wirelessly transmitted via WiFi to display in real-time on a Google Sheet and stored as logs on the same platform for further analysis.

In addition, an IR sensor connected to the ESP-32 microcontroller was placed on a stand in a manner that it could be activated by a black strip acting as a circular radius. As the black strip moved across the path of the IR sensor, it triggered the sensor, enabling precise data collection and synchronization with the circular motion of the turntable.

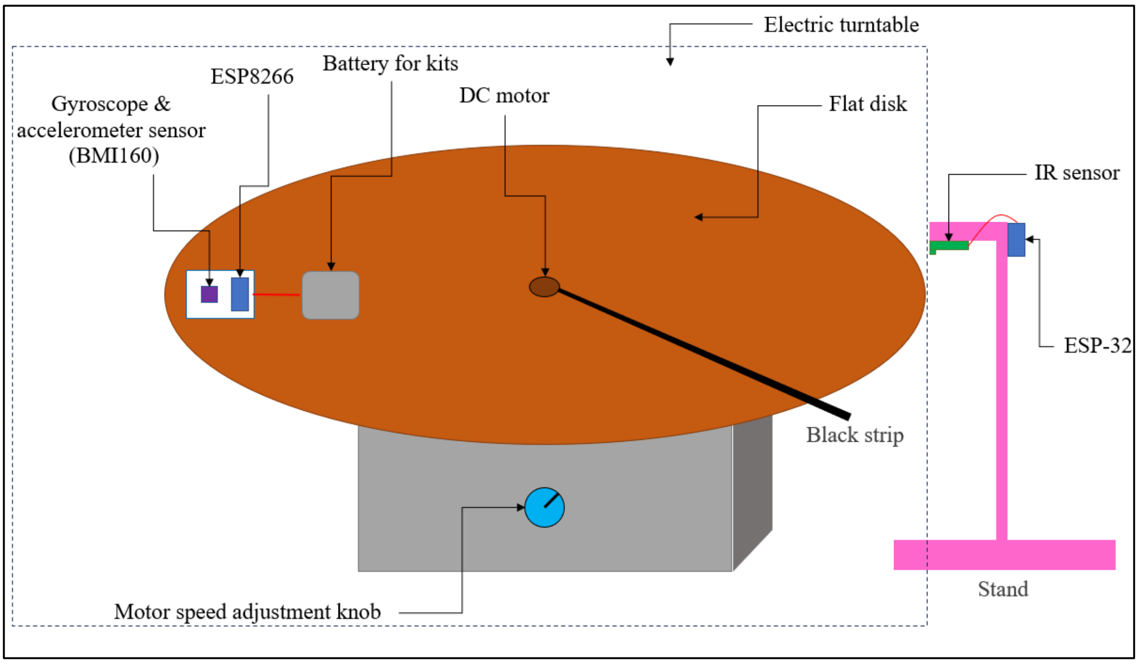

Figure 3 Components of the experimental kit - electric turntable and sensors diagram.

Figure 4 The sensor set was installed onto the turntable ('A' - top view and 'B' - front view).

The experimental process involved several steps. Initially, a set of gyroscope-accelerometer sensors was carefully placed on the electric turntable, with the distance between the center of the circle and the center of the sensor measured as the radius of circular motion. The radius was set at 10.0 cm initially. Next, the electric turntable was switched on, and the rotational speed of the electric motor was adjusted based on the period obtained from the IR sensor. The starting point for the rotational speed was approximately 1400 ms/turn. During the experiment, a total of 100 pairs of angular velocity and centripetal acceleration data were collected, along with the corresponding periods of circular motion. Once all three quantities of information were obtained, the rotational speed of the electric motor was adjusted to 1600, 2000, 2400, and 2700 ms/turn, respectively. The same process of data collection was repeated for each of these rotational speeds. Furthermore, the position of the gyroscope-acceleration sensor set was modified to a radius of 15. 0 cm and 20.0 cm, respectively. The angular velocities, centripetal accelerations, and periods were collected at these two new radii, with the same five levels of electric motor rotation speed as before. This systematic approach allowed for comprehensive data collection across various radii and rotational speeds, enabling a thorough investigation of the relationship between angular velocity, centripetal acceleration, and period in circular motion.

The procedure for analyzing the experimental data consisted of two main parts. In the first part, the focus was on evaluating the consistency between the angular velocity obtained from the gyroscope and the period measured by the IR sensor. To achieve this, the rotational speed of the turntable was systematically varied, and the corresponding measurements of angular velocity and period were recorded. By comparing these measurements, the consistency between the two quantities was assessed. In the second part, the objective was to investigate the consistency between the angular velocity measured by the gyroscope and the centripetal acceleration derived from the accelerometer. This investigation involved varying both the radius and the rotation speed of the turntable. Data on angular velocity, centripetal acceleration, and the corresponding experimental conditions (radius and rotation speed) were collected. By analyzing this data, the relationship between angular velocity and centripetal acceleration was explored, and the consistency between these variables was evaluated. Through the analysis of the obtained data in both parts, the researchers were able to gain insights into the relationships and consistencies between period, angular velocity, and centripetal acceleration in the context of circular motion.

Results and Discussion

An array of sensors, comprising gyroscopes, acceleration sensors, and infrared sensors, was carefully assembled and installed on the turntable. This instrumentation has proven to be well-suited for capturing diverse parameters associated with horizontal circular motion, including time periods, angular velocities, and centripetal accelerations. The collected data from these sensors is seamlessly transmitted to the designated Google Sheets platform, facilitating efficient storage and analysis of the acquired quantities.

In the initial phase of the experiment, a comparison is made between the angular velocity, as determined by the gyroscope, and the corresponding period, as measured by the infrared sensor. This comparison is conducted by systematically varying the rotational speed of the turntable. To capture the necessary data, a pair of sensors is positioned at radii of 10.0, 15.0, and 20.0 cm. The rotation speeds employed for data collection are approximately 1400, 1600, 2000, 2400 and 2700 ms/turn. Table 1 presents the average values of the period and angular velocity, obtained from 100 pairs of data readings recorded by the gyroscope and accelerometer sensors. The table offers information on the average values of these parameters as measured by the respective sensors. In the table, the variable T represents the average period, ω represents the average angular velocity, and the subscript numbers 1 and 2 indicate the quantities measured by the IR sensor and gyroscope sensor, respectively.

Table 1 Average of period and angular velocity collected using ESP-32 with in a period range of 1400-2700 ms.

Rotation speeds (approximately, ms/turn)	Radius (cm)	IR sensor$_1$			Gyroscope$_2$		Difference of average
		T_1 (ms)	ω_1 (rad/s)	S.D. of ω_1	ω_1 (rad/s)	S.D. of ω_2	ω (rad/s)
1400	10.0	1270	4.95	0.01	4.91	0.07	0.04
	15.0	1467	4.28	0.06	4.27	0.09	0.01
	20.0	1387	4.53	0.04	4.49	0.08	0.04
1600	10.0	1576	3.99	0.02	3.98	0.08	0.01
	15.0	1661	3.78	0.05	3.78	0.10	0.01
	20.0	1623	3.87	0.03	3.86	0.08	0.01
2000	10.0	1964	3.20	0.04	3.18	0.10	0.02
	15.0	1997	3.15	0.03	3.13	0.10	0.01
	20.0	2046	3.07	0.01	3.07	0.10	0.00
2400	10.0	2351	2.67	0.02	2.66	0.13	0.02
	15.0	2345	2.68	0.02	2.67	0.12	0.00
	20.0	2353	2.67	0.01	2.67	0.11	0.00
2700	10.0	2681	2.34	0.04	2.29	0.23	0.05
	15.0	2658	2.36	0.02	2.35	0.19	0.02
	20.0	2698	2.33	0.02	2.32	0.14	0.01

The data presented in Table 1 reveal that there is no substantial disparity between the angular velocities obtained from both sensors. This observation is further supported by the small difference observed in the average angular velocities. Specifically, the maximum difference in average angular velocity is measured at 0.05 rad/s, which falls within an acceptable range. Consequently, these findings suggest that the relationship between the period and angular velocity can be accurately represented using equation $\omega = 2\pi/T$.

In the second part of the experiment, the focus is on comparing the angular velocity and centripetal acceleration measurements obtained from the gyroscope-accelerometer sensor (BMI160). This comparison involves systematically varying both the radius of circular motion and the rotation speed (period) of the turntable to different values. The aim is to examine the relationship between these two parameters under various experimental conditions. Table 2 provides detailed information regarding this comparison. In the table, the variable a_c represents the average centripetal acceleration, while the subscript numbers 2 and 3 indicate the quantities measured by the gyroscope and accelerometer sensors, respectively. The table allows for a comprehensive analysis of the relationship between angular velocity and centripetal acceleration under different experimental settings.

Table 2 Average of angular velocity and centripetal acceleration collected using ESP8266 at a period of 1400-2700 ms.

Rotation speeds (approximately, ms/turn)	**Radius (cm)**	**Gyroscope$_2$**			**Accelerometer$_3$**		**Mean difference**	**S.D. of the differences**	**P-value (t-test) at alpha 0.05**
		ω_2 **(rad/s)**	a_{c2} **(m/s^2)**	**S.D. of** a_{c2}	a_{c3} **(m/s^2)**	**S.D. of** a_{c3}	a_c **(m/s^2)**	a_c **(m/s^2)**	
1400	10.0	4.91	2.411	0.073	2.398	0.109	0.065	0.050	0.125
	15.0	4.33	2.812	0.148	2.807	0.169	0.074	0.057	0.601
	20.0	4.49	4.031	0.149	4.038	0.167	0.095	0.074	0.564
1600	10.0	3.98	1.582	0.066	1.589	0.065	0.046	0.035	0.281
	15.0	3.78	2.142	0.116	2.143	0.117	0.046	0.043	0.872
	20.0	3.86	2.978	0.130	2.970	0.134	0.059	0.049	0.311
2000	10.0	3.18	1.010	0.067	1.008	0.102	0.059	0.044	0.773
	15.0	3.13	1.475	0.090	1.460	0.104	0.081	0.068	0.161
	20.0	3.07	1.891	0.127	1.887	0.134	0.079	0.057	0.672
2400	10.0	2.66	0.707	0.071	0.687	0.159	0.114	0.092	0.176
	15.0	2.67	1.075	0.095	1.075	0.141	0.097	0.077	0.959
	20.0	2.67	1.428	0.112	1.434	0.140	0.106	0.083	0.640
2700	10.0	2.29	0.530	0.104	0.505	0.334	0.236	0.184	0.405
	15.0	2.35	0.830	0.131	0.798	0.141	0.197	0.141	0.187
	20.0	2.30	1.083	0.128	1.065	0.184	0.129	0.115	0.284

Table 2 presents an analysis of the angular velocity and centripetal acceleration obtained from the gyroscope-acceleration sensor, with 100 pairs of measurements. The table includes the mean, standard deviation, mean difference, standard deviation of the differences, and the p-value from a t-test. The primary objective of the table is to assess the accuracy and reliability between the two sensors. The mean difference represents the average deviation between the data sets, providing an overall measure of disagreement. It helps to understand the average level of deviation between the measurements. The standard deviation of the differences quantifies the spread or variability in the measurements, allowing for the evaluation of disagreement or inconsistency between the data sets. A higher standard deviation indicates a greater level of disagreement or inconsistency. Upon analyzing the table, it is evident that the majority of the data exhibits relatively low mean differences and standard deviations of the differences. This indicates that the angular velocity from the gyroscope and the centripetal acceleration from the accelerometer are consistent with each other. However, in Table 2, with an approximate speed of 2700 ms/turn and radii of 10.0 cm and 15.0 cm, and with an approximate speed of of 2400 ms/turn and a radius of 10.0 cm, the mean difference and standard deviation of the differences are higher compared to the other data. This suggests a relatively high level of disagreement or inconsistency between the angular velocity and centripetal acceleration measurements in these specific conditions.

Further examination by the researcher revealed that the higher mean difference and standard deviation of the differences in Table 2 were due to vibrations caused by the electric motor at low frequencies. The researcher observed experiments conducted at both low and high frequencies and identified that the vibrations in the low frequency range were the cause of the higher disagreement and inconsistency in the data. Therefore, it is advised to avoid conducting experiments in the low frequency range of the electric motor when utilizing this setup to demonstrate the relationship between angular velocity and centripetal acceleration in real-time data analysis.

Furthermore, we conducted a paired two-sample t-test [6] to compare the means of the centripetal acceleration obtained from the gyroscope and accelerometer. The null hypothesis (H_0) was formulated to state that there is no significant difference in the means of the two-sensor data (H_0 = 0), with a significance level of 0.05. Regardless of the radius or rotational speed used, the calculated p-value was found to be greater than the significance level (> 0.05). Consequently, we accept the null hypothesis, indicating that the mean accelerations towards the center from both sensors are not significantly different.

In the physics laboratory, our main objective was to visually demonstrate the relationship between angular velocity and centripetal acceleration to the students, as described by equation (2). To accomplish this, we created a graph illustrating the relationship between the squared angular velocity obtained from the gyroscope and the centripetal acceleration measured by the accelerometer. The graph was generated using averaged values obtained from five experimental trials, where the angular velocities were varied while keeping the radii constant. The aim was to assess the reliability of the sensor in accurately depicting the relationship between different quantities involved in circular motion within a real laboratory setting. Figure 5 displays the results obtained when the sensor set was positioned at a radius of 10.0 cm. The graph clearly exhibits a strong linear trend, as supported by the adjusted R-squared value approaching 0.99 (close to 1). This indicates a high degree of correlation between the centripetal acceleration and the squared angular velocity, as expressed by equation (2): $a_c = r\left(\omega^2\right)$. Moreover, the slope of the graph corresponds to 0.100 m, which matches the installed radius. These findings highlight the effectiveness of both the gyroscope and accelerometer in accurately measuring physical quantities and demonstrating their interconnectedness within the context of circular motion.

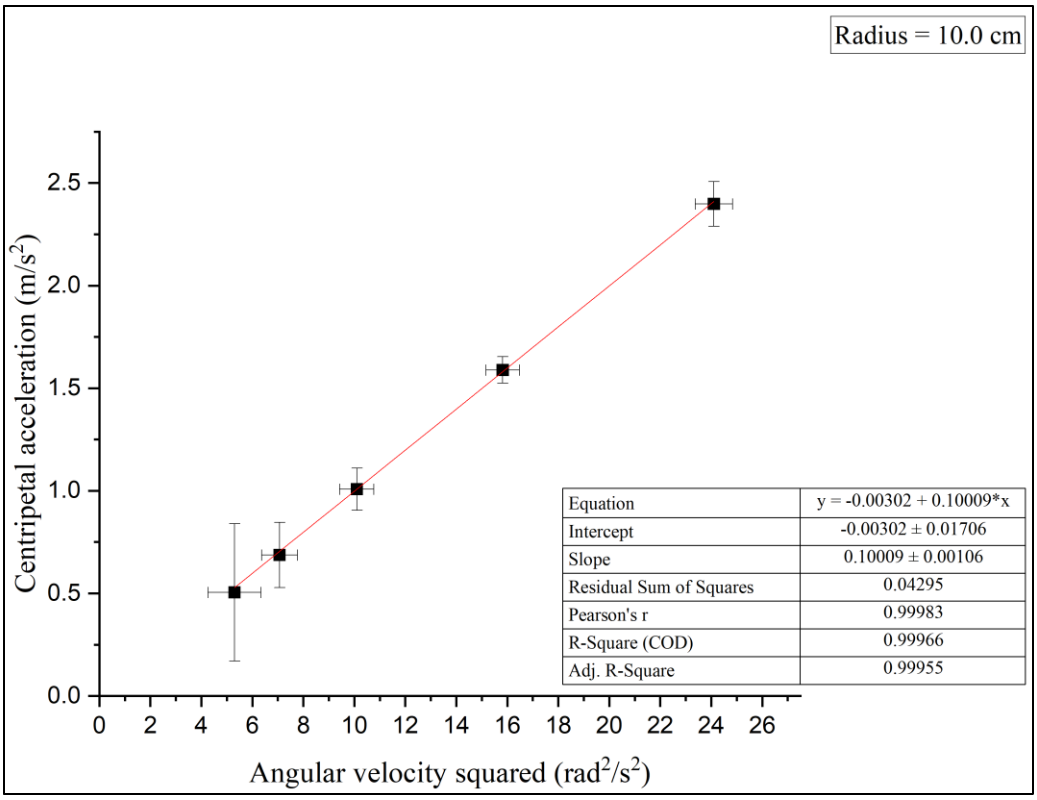

Figure 5 Graph of angular velocity squared relations with centripetal acceleration at a radius of 10.0 cm.

In addition to the experiment conducted with a radius of 10.0 cm, Figures 6 and 7 display the experimental results obtained with radii of 15.0 cm and 20.0 cm, respectively. Similar to the previous findings, these graphs also demonstrate a linear trend. This observation is supported by the adjusted R-squared values, which were close to 1 (above 0.99 for both cases), and the slopes of the graphs, which closely match the respective radii used for sensor placement (0.151 m and 0.201 m). These results further affirm the capability of both the gyroscope and accelerometer to accurately measure physical quantities and effectively portray their relationships.

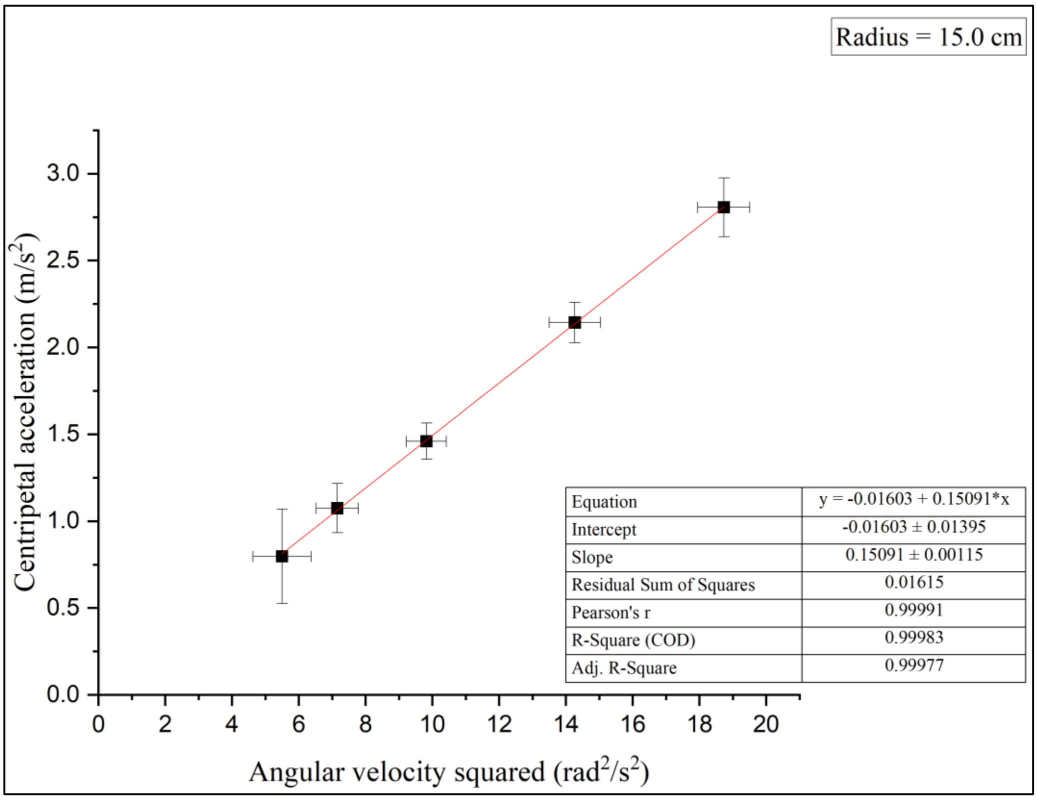

Figure 6 Graph of angular velocity squared relations with centripetal acceleration at a radius of 15.0 cm.

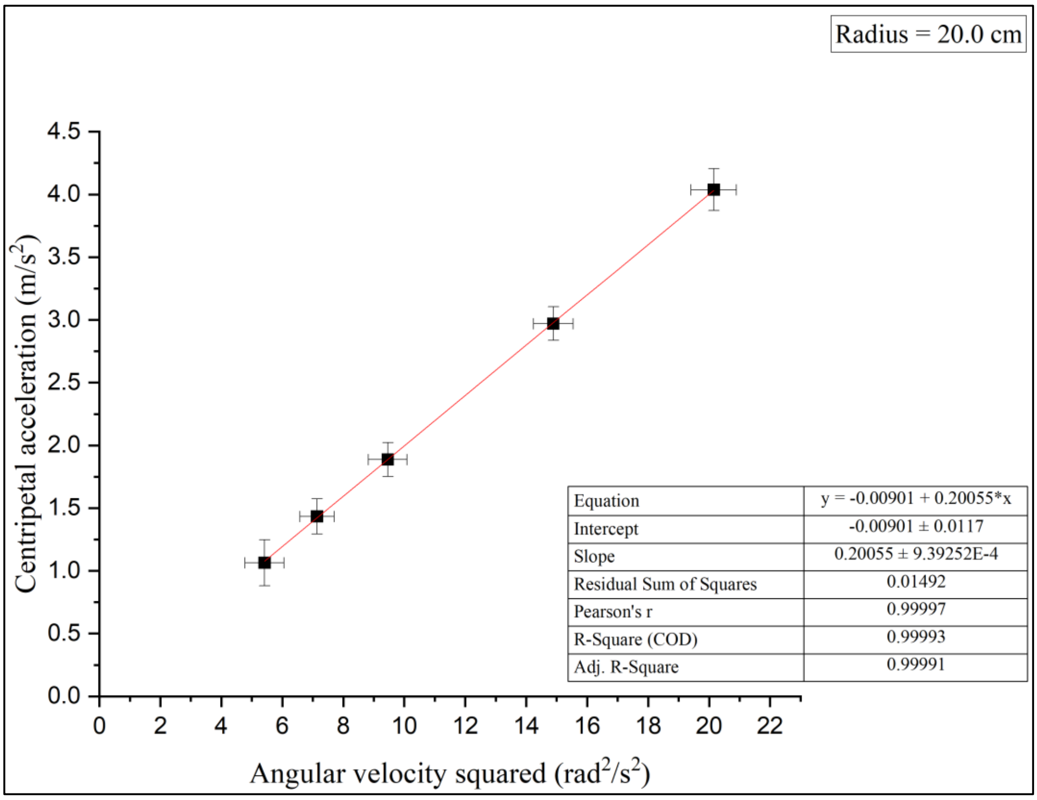

Figure 7 Graph of angular velocity squared relations with centripetal acceleration at a radius of 20.0 cm.

Based on the obtained experimental results, the sensor kit utilized in the second part of the experiment proves to be highly suitable for demonstrating horizontal circular motion. Moreover, it allows for the clear depiction of the relationship between the measured parameters, as described by equation (2). Notably, the accelerometer sensor exhibits excellent performance, particularly when employed at larger radii and higher rotational speeds. This finding suggests that the sensor kit is capable of accurately capturing the relevant data and effectively illustrating the desired relationship between the variables of interest.

Based on the findings from both experimental trials, it is evident that certain uncertainties arise due to various factors, including the positioning of the sensor on the turntable, vibrations caused by the electric motor, and the precision of the radius-measuring instrument. However, it is important to note that the observed uncertainties fall within an acceptable range. This indicates that the equipment utilized in these experiments is reliable and suitable for experimental use in the physics laboratory. Despite the presence of these uncertainties, the obtained data can still be considered valid and valuable for further analysis and scientific investigations.

To calculate the centripetal force, equation (1) can be employed in conjunction with additional measurements of the mass of the sensor kit and the experimentally determined centripetal acceleration. This relationship allows for the quantification of the centripetal force acting on the system under investigation.

Conclusions

Based on the results of the experiments and subsequent data analysis, it has been established that utilizing a set of sensors with the ESP8266 as a controller is an effective and cost-efficient approach for demonstrating the relationship between various variables associated with horizontal circular motion. The affordability of these sensors and the ESP8266 falls within the desired budget range for researchers. Furthermore, despite their relatively low cost, this setup exhibits superior precision and accuracy compared to the high school physics experiment sets currently in use. The incorporation of this cost-effective solution into the curriculum for horizontal circular motion lessons offers several benefits for students. Firstly, it simulates uniform circular motion with minimal variation in angular velocity during each experiment. This reduces discrepancies in the timing of object movement compared to swinging a rope or manually performing circular motions. Secondly, it minimizes the inclination of the plane of horizontal circular motion, leading to more consistent results. These factors contribute to the generation of visually appealing graphs that clearly depict the relationship between different quantities in circular motion. This enhanced graph representation allows students to better comprehend and observe the relationships between various quantities associated with circular motion. Overall, this cost-effective experimental setup presents a valuable and impactful tool for enhancing students' understanding of circular motion concepts in the classroom.

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