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STEM Education of Kinematics and Dynamics Using Arduino

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Ever increasing technological progress opens novel opportunities concerning educational activities, and the ability to use the technology effectively is one of the 21st century's most demanding skills.[1,2] The Partnership Forum for 21st-Century Skills (P21) states that no organization can achieve satisfying results without using technology and therefore the use of technology particularly in schools should be at the highest level.[3] Some novel teaching methods have recently emerged based on technological developments, such as STEM education, which is based on the integration of science, technology, engineering, and mathematics.[4] In this study, the motion of a body connected to a pulley system is analyzed by using an Arduino microprocessor and also related mathematical equations. Arduino is a programming platform on which various electronic elements can be connected.[5] There are various Arduino compatible sensors (sound, light, distance, temperature, etc.) that can be coded for their intended use. Due to its cost effectiveness, this technological instrument can be used as a measurement tool in many physics experiments.[6-12] In this work, the time-varying data of the position of the moving object is determined using the HC-SR04 ultrasonic distance sensor (see Fig. 1). The HC-SR04 distance sensor can determine the distance of the obstacle from the sensor when the transmitted signal is reflected from an obstacle and returned to the sensor,[13] and the Arduino IDE computer program is used to load the corresponding codes into the Arduino and to retrieve the incoming data.[14]

Theory

The theoretical resolution is managed under two basic assumptions: firstly, the rotational inertia of the pulleys will be ignored since their mass is small, and secondly, the friction of the system is ignored since the ropes and pulleys are carefully lubricated before the operation.

Newton's second law of dynamics, $F_{net} = ma$, can be rewritten for the first body, m_1, as follows (see Fig. 2):

$$G_1 - T = m_1 a_1. \tag{1}$$

Similarly, the equation of motion for m_2 can be expressed as follows:

$$2T - (G_2 + G_r) = (m_2 + m_r)a_2, \tag{2}$$

where T denotes the tensile force on the string, G_1 is the weight of m_1, G_2 is the weight of m_2, and G_r denotes the weight of the moving pulley. Additionally, it is well known that $x_1 = 2x_2$, hence, relating the accelerations of the two bodies, $a_1 = 2a_2$ can be written. In the following resolution, $a_1 = 2a$ and $a_2 = a$ are selected, and then it is straightforward to obtain the acceleration as

$$a = \frac{2G_1 - (G_2 + G_r)}{(4m_1 + m_2 + m_r)}. \tag{3}$$

Knowing the masses of m_1, m_2, and m_r measured with precision scales and also G_1, G_2, and G_r, the corresponding accelerations can theoretically be estimated. The distance-time relation is then given by the kinematics equation of

$$x = x_0 + v_0 t \pm \frac{1}{2} a t^2, \tag{4}$$

where x_0 denotes the initial position, v_0 denotes the initial velocity, and a denotes the acceleration of the body.

Experimental setup

The experimental components required are a fixed pulley, a moving pulley, an ultrasonic distance sensor, an Arduino Uno, a computer, two objects with certain masses, and connection cables, as shown in Fig. 1.

The experimental setup employed throughout the work is composed of two standing rods, one fixed pulley, one movable pulley, two masses, and a complete Arduino system including the computer. A photo of the whole setup is shown in Fig. 2.

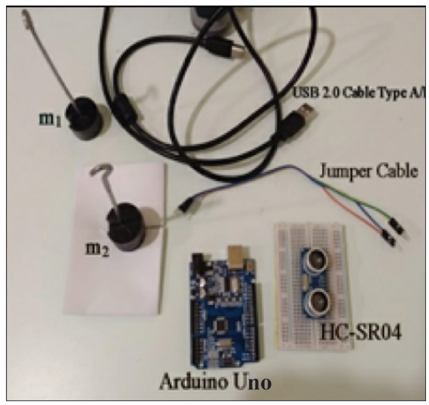

Fig. 1. Photo of the components.

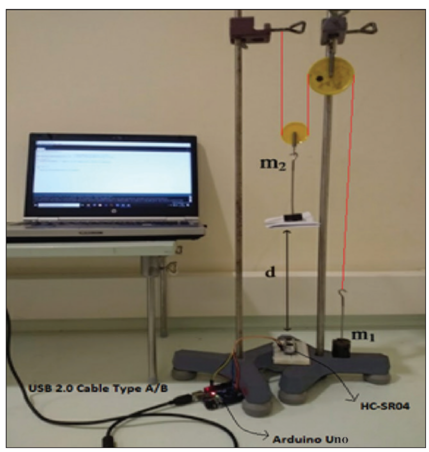

Fig. 2. Photo of the experimental setup including the two pulleys, two masses, and complete Arduino system.

The Arduino system is set to measure distance d between the moving object m_2 and the Arduino distance sensor. The distance sensor is positioned vertically below the mass m_2, connected to the moving pulley, and the base area of the m_2 body is enlarged by using a piece of paper to ensure more accurate measurements. There are a transmitter and a receiver side by side on the distance sensor. The signal sent from the transmitter is reflected from the obstacle and comes to the receiver. At this point, the path followed by the signal is not straight, but conical with respect to the sensor. The piece of paper mounted under the mass m_2 was used for the sensor to take measurements properly due to the conical nature of the HC-SR04 sensor.

Data collection details

In order to collect the data, initially the HC-SR04 ultrasonic distance sensor and Arduino Uno are connected to each other in the following manner: VCC to 5V, GND to GND, ECHO to 12, and TRIG to 13. After the connections, the relevant code (see appendix) is loaded into Arduino. Suppose that the direction of movement of mass m_1 is downward upon release. Then it is useful to push mass m_1 slightly upwards initially; naturally after a short while, mass m_1 stops, making the distance (d) take on its smallest value, and from this moment mass m_1 moves downward and the system starts to move with appropriate acceleration value.The mass m_1 could also be released directly without pushing it up; however, the data taken over Arduino are taken every 50 ms and the distances are printed with an accuracy of 0.01 cm; in this case, the position and time values of the system start to be recorded with higher error margins. Hence, the first value to be selected is the smallest value of d, and successive positions are selected as shown in the Fig. 3.

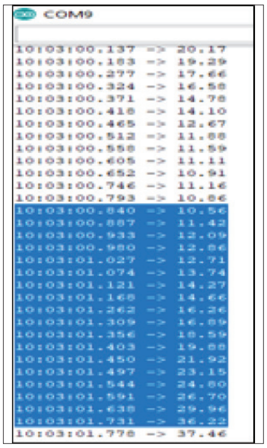

Fig. 3. Original data obtained from Arduino IDE.

If the selected data are copied directly to Excel, they are taken into a single column so some data conversion must be performed (such as deleting the hours and minutes and extraneous symbols).

Once the data are in an appropriate two-column format in Excel a scatter plot is drawn. A trend line is added to the chart and right-clicking on the line will go to the formatting menu. Here, $x = At^2 + Bt + C$, polynomial option is selected, and the equation is asked to be shown on the graph.

Results

The pulley-mass systems are run a number of times for various mass couples and the distance of the m_2 measured as a function of time. The first measurement that is performed for the $m_1 = 61$ g and $m_2 = 101$ g mass couples is shown in Fig. 4.

Table I. The overall results obtained both experimentally and theoretically and the percentage deviations.

m_1 (g)	m_2 (g)	a (m/s^2) Experimental	Theoretical	Percentage Deviation (%)
101	60	3.20	3.00	6.70
141	141	1.95	1.96	0.51
61	101	0.66	0.59	11.00
60	141	-0.48	-0.54	11.10

In order to estimate the experimental acceleration of m_2, the obtained data are curve fitted and the outcome is given by $x = 32.8$ cm/s/s $t^2 - 68.7$ cm/s $t + 38.1$ cm. The data show a good agreement with the theoretical expression that is $x = x_0 + v_0\ t \pm (1/2)\ at^2$. This effort gives an acceleration of m_2 as $a = 65.6$ cm/s^2.

The overall results for various mass couples obtained experimentally and theoretically are given in Table I. The experimental results are extracted from the curve fits of the experimental graphs. The theoretical acceleration values are basically calculated from Eq. (3) by substituting the corresponding values within the equation.

As can be seen in Table I, in repeated applications with different masses, results consistent with theoretical calculations have been obtained. In addition, the negative result shows that the obtained experimental results are also suitable for the vector nature of the acceleration, and therefore the vector structure of the acceleration can be emphasized with such a study.

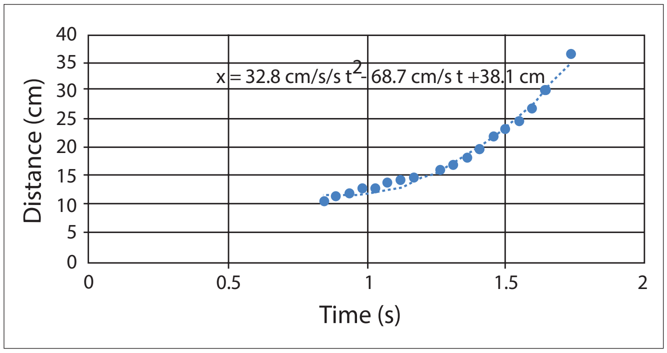

Fig. 4. The distance vs. time for the $m_1 = 61$ g and $m_2 = 101$ g mass couples.

Conclusion

This study offers an alternative approach to teach important topics such as kinematics, dynamics, and coding as a part of STEM education. The theoretical dynamics and kinematics equations can practically be validated experimentally for teaching purposes. More specifically, the students can analyze the position-time graphs of linear motion as a part of a pulley-mass system by performing the experiment, and also mathematical operations hence can calculate the acceleration of a complex system using dynamics laws. This study is beneficial for educational purposes because of its low cost and ease of establishment.

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Appendix. Code uploaded to Arduino

```
int trigPin = 13;
int echoPin = 12;

long t;
long distance;

void setup(){
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin,INPUT);
  Serial.begin(9600);
}
void loop()
{
  digitalWrite(trigPin, LOW);
  delayMicroseconds(5);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);
  t = pulseIn(echoPin, HIGH);
  distance= t /29.1/2;
  Serial.println(distance);
  delay(50);
```