Teaching equipment of newton's second law

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Abstract. Mechanic is the branch of physics that is responsible for the study of the movement and balance of bodies in a system, within this can also be considered the bodies at rest. For the first case the scientist Isaac Newton considered the study of the movement of bodies, where he defines that any physical system which is subjected to different actions, as long as such actions are not nullified, will result in a change in the state of the body. The force is the magnitude that quantitatively measures the intensity, direction and direction of that interactions, having said that, if the summation of all forces of a system is different from zero, it can be concluded that the system will be in motion and therefore have an associated acceleration. Based on the above definition, was executed by the research group Design and Construction of Prototypes for Demonstration Experiments (DICOPED) in the design and construction of a prototype that allows to verify the Newton’s Second Law, looking to develop an autonomous, robust and low-cost prototype, that allows the use of the technology and tools present in the means, encourage and facilitate the teaching of basic concepts but no less important of physics to students of basic and higher education.

1. Introduction
Developing equipment for physics education, is a little-explored field by academic world, but it is a valuable tool to achieve entrenching basic physics concepts. DICOPED research group has worked on the development of teaching equipment that allows teachers in the classroom or laboratories to show experimental forming of physical phenomena. Likewise, the use of the human and technological resources present in the means, allow to develop autonomous prototypes that satisfy the present needs in educational environments at the local, national level and why not in the international future.

2. Methodological Design
Four phases were proposed for the development of the autonomous prototype by the experimental demonstration of Newton's Second Law:

• The first is based on the understanding of the theoretical concepts of Newton's Second Law.
• The second consists of the design and construction of a mechanical model that allows experimental verification of Newton's Second Law.
• The third is based on electronic development and coding of electronic system akin to the requirements of mechanical assembly.
• The fourth phase consists of the development of a guide which allows to experimentally verify the results obtained with the completed prototype. The detailed development will be shown below.

3. Theoretical Framework

3.1 Newton's Second Law
Newton's Second Law or Law of Force is also known as the Fundamental Law of Dynamics, it determines a proportional relationship between force and variation of the amount of movement or linear moment of a body [1].

This law declares that when an object experiment a force, that force causes an acceleration in the object. The previous acceleration is therefore proportional to the intensity of the force, going in direction of the applied force and it is inversely proportional to the mass of the object.

Therefore, if a resulting non-zero force acts on a moving body, this force will modify the state of movement of the body by changing the direction or magnitude of its speed.

3.2 Amount of Movement
The amount of movement, linear moment or momentum is a vector magnitude, which in classical mechanics is defined as the product of the body mass and its speed at a given moment [2] (see Figure 1).

\[ \mathbf{F} = m \mathbf{a} = \frac{d \mathbf{v}}{dt} \]

From the above it can be concluded that a body in motion has a non-zero linear momentum, otherwise the body is at rest. The units of linear momentum in the international system are .

The amount of movement is a vector magnitude, that is, to describe it, you must know its magnitude, direction, which has for direction the same direction of the velocity of the body. For this reason, it is sometimes confused with speed. This is not correct since the moment relates the mass of the object which considerably influences the amount of movement of the body.

It is important to keep in mind that the original form of Newton's Second Law directly relates the concept of linear momentum and the resulting net force acting on it, for inertial frames of reference and systems of constant mass, since:

\[ \mathbf{F} = m \frac{d \mathbf{v}}{dt} \]

Therefore, knowing that \( m \mathbf{v} \) is \( \mathbf{p} \), then the previous expression is understood as the change in time of the linear momentum of a particle is equal to the resulting force acting on it, the above can be written as:

\[ \sum \mathbf{F} = \frac{d \mathbf{p}}{dt} \]

It can be deduced that the resulting force is zero, the linear moment of the particle must be constant. [3]
4. Design and Construction of Prototype

Next, the process of the design and construction of the prototype will be detailed, for which a preliminary analysis was carried out for the adequate selection of materials and available technology to build a robust and low-cost prototype.

4.1 Mechanical design of the prototype

The mechanical design of the prototype consists of a plane with an approximate length of 60 cm, the surface of the plane has a rail on which a variable-mass cart will move (inserting masses on the vertical axis that the cart has in its upper part), for this there is a system of copper wheels which, when moving on a low friction surface, allow to avoid energy loss due to friction in the movement of the system, in Figure 2 the described assembly is shown.

![Figure 2, Base with rail and mobile cart](image)

Likewise, the system has a 4 cm diameter pulley which is shown in Figure 3, which rotates around a low friction axis, said pulley will be complemented with an adhesive that will allow to determine the angular acceleration of the movement of the system once the device is docked.

![Figure 3, Marked pulley.](image)

To complete the mechanical system, there is a universal mass support, which allows varying the mass that is suspended in the air, which can be seen in Figure 4.
In the previous figure you can see the equipment, the CNY70 sensor is located at the back of the pulley, its power supply and output are at the other end of the rail, which facilitates and avoids the interference of cables or connectors in movement, this can be seen in Figure 5.

Likewise, it was necessary to design a box that would be coupled to the electronic part of the prototype, for this acrylic was used which is a resistant and easy-to-use material, in this box the Arduino was housed in conjunction with the Shield Key-Pad that allows user interaction with the system.

Based on the CorelDraw design application, which offers powerful drawing, text handling, vectorization, color separation, and special effects features, the prototype parts were designed. The designed parts are described below (see Figure 6, Figure 7, Figure 8, Figure 9).
4.2 Electronic prototype design
The prototype developed consists of a control platform based on Arduino, which is linked to a Shield containing the keyboard and the LCD screen, this device allows the user to interact with the Arduino and define the application execution flow (see Figure. 10).

Figure 7, Top and bottom caps.

Figure 8, Left and right side covers.

Figure 9, Box assembled.

Figure 10, Arduino – Shield LCD Keyboard.
The electronic design implemented consists of the aforementioned element and a CNY70 sensor that allows to measure the time it takes for the rotation of the pulley present at one of the ends of the prototype. The signal delivered by the CNY70 sensor, which is an IR emitter and receiver type sensor, is shown in the following image (see Figure. 11).

![Figure 11](image1)

Figure 11, Output signal.

Since the above signal is not a clean signal, processing was performed to improve the precision in taking experimental data. For this, a Smith Trigger was used, which acts as an ideal conditioner since it transforms the sensor output signal to pure logic levels.

For this application, a positive feedback op amp was used. Reference levels are adjusted with resistance. Normally NOT gates with Schmitt trigger with TTL technology are used. The symbol inside the triangle in Figure. 12 denotes that the logic gate is Schmitt-trigger [4].

![Figure 12](image2)

Figure 12, Smith Trigger symbol.

The arrangement of the following figure provides a good response of the output signal since the transfer curve shows a behavior like the one shown in the figure (see Figure. 13).

![Figure 13](image3)

Figure 13, Circuit to eliminate Schmitt-trigger noise - Transfer curve.

Finally, after performing the described processing, an output signal is obtained in accordance with the desired requirements for the application (see Figure. 14).
ARES, a Proteus tool suitable for the design of printed circuit boards (PCBs), was used to design the printed circuit board. It is fully integrated with the ISIS tool.

Once the electronic schema has been designed in ISIS (see Figure. 15), the list of networks (NETLIST) is automatically generated. A network is a group of pins interconnected to each other and the network list is a list of all the networks that make up the layout. ARES receives this list of networks to design the printed circuit. In this way, it is ensured that the board will have the pins connected to each other in an identical way as defined in the electronic diagram.

Below is the result obtained in the ARES of the circuit designed in PROTEUS (see Figure. 16).

Finally, when printing the circuit, the tracks that must be burned on the virgin copper card are obtained to carry out the final assembly of the circuit (see Figure. 17).
5. Results
Finally, the result is a prototype that allows experimental verification of Newton's Second Law, for this, in addition to the design and construction of the prototype, a guide for experimental practice was developed, which is shown below.

Newton's Second Law Experimental Practice Guide

5.1 Introduction
In every physical system, a body will remain in a state of rest or movement at constant speed unless an action occurs that alters its state. From the above, it can be concluded that a force is the measure of a physical interaction that affects the state of movement of the bodies present in a system, these changes in movement are associated with a change in speed which leads to the definition acceleration.

Based on the above, it can be affirmed that there must be some relationship between the concepts of force and acceleration, as well as the study of the behavior of this phenomenon that has an answer in Newton's second law.

5.2 Objectives
i. Experimentally determine the acceleration of a body, when the system presents a sum of forces other than 0.
ii. Construct a graph of the angular position based on time.
iii. Analyze and describe the behavior of a system from a graph.
iv. Give experimental support to the mathematical relationship between force, mass and acceleration.

6. Conceptual Framework

6.1. Newton's Second Law
Newton's Second Law states that the acceleration of an object is proportional to the net force applied to it, which can be expressed mathematically as:

$$\vec{F} = M\vec{a}$$

(4)

Where:
- $\vec{F} \rightarrow$ Net force on the system.
- $M \rightarrow$ System mass.
- $\ddot{a} \rightarrow$ Acceleration experienced by the system.

This acceleration is a vector quantity and its direction is given by the direction of the resulting net force, that is, the force resulting from the sum of the forces present in the system [5].

In this practice, the previous statement will be verified experimentally, for this we will take a mass object $m_2$ and it will accelerate generating on it a known force. This will be done by tying an inextensible thread of negligible mass at one end of the mass, and completing the system with a pulley that will allow suspending a mass $m_1$ vertically, which will result in a tension $T$ on the thread, which will finally be the force on the mass $m_2$, the system described in the Figure 1.

![Figure 18. Equipment schematic.](image)

The system is made up of two bodies, which are initially at rest, once they are released, they accelerate due to the existing forces in the system. If the free-body diagram for the system is made, the following analysis is obtained.

### 6.1.1. Theoretical analysis of movement

For the analysis of the system, the mass of the pulley and the negligible thread must be assumed as the first measurement. Once this has been stated, the force analysis is carried out according to Newton's laws.

**Sum of forces for mass $m_2$:**

$$ T_1 - F_r = m_2a $$

(5)

**Sum of forces for the mass $m_1$:**

$$ m_1g - T_2 = m_1a $$

(6)

Where is considered $F_r$ as the friction force between the carriage and the rail surface, $m_2$ is the mass of the car, $T_1$ is the tension of the thread on the carriage, $m_1$ corresponds to the suspended mass on the universal bracket, the tension $T_2$ is directly related to the hanging mass and $a$ is the acceleration of the system. From the previous analysis, when operating the equations, we obtain:

$$ a = \frac{m_1g - F_r}{m_1 + m_2} $$

(7)

Once the analysis has been carried out on the bodies, the analysis is carried out on the pulley, assuming that the pulley has a non-negligible mass, therefore, when applying Newton's laws, we arrive at:
\[ T_1 - F_R = m_2 \alpha \quad (8) \]
\[ m_1 g - T_2 = m_1 \alpha \quad (9) \]
\[ T_1 - T_2 = \frac{I \alpha}{R} = \frac{I \alpha}{R^2} \quad (10) \]

In such a way that in the previous expression $R$ it is the radius of the pulley, $\alpha$ is the angular acceleration of the pulley and $I$ is the moment of inertia of the pulley $\left(I = \frac{1}{2} Mr^2\right)$. When performing the respective analysis and solving the acceleration of the previous equations, we obtain:

\[ a = \frac{m_1 g - F_R}{m_1 + m_2 + \frac{I}{R^2}} \quad (11) \]

Finally, the experimental study of the system is carried out as a function of mass, working with the expression:

\[ \left(m_1 + m_2 + \frac{I}{R^2}\right) a = m_1 g - F_R \quad (12) \]

Plotting the left side of the equality as a function of yields a curve that resembles a mathematical expression similar to the one shown below.

\[ f(x) = gx - F_R \quad (13) \]

Which corresponds to the equation of a line, where the friction force would be the cut of the line with the vertical axis and its slope would be directly related to the value of gravity. For greater reliability of the data obtained, it is necessary to determine the correlation coefficient to determine the correspondence and trend of the measurements. It is important to keep in mind that the suspended mass must be large enough compared to the mass of the rope to obtain good experimental results.

6.2. Procedure

6.2.1. Assembly of Equipment

i. With the rail and the control box identified, proceed to place the equipment on a horizontal table, verify that it is level (with the device located on the rail).

ii. Identify output 1 of the control box, connect the USB cable from the control box to the sensor connector located on the pulley.

iii. Take the power source to energize the control box through the 5 V input and connect it to 110 V.

iv. Place the low-friction cart at the end opposite the pulley on the track and tie a string to one end. The other end must be free for mass support.

v. Identify the mass support and measure its initial mass, keep the data.

vi. Put a mass of 250 grams in the cart and measure the total mass of the cart, keep the value taken.

vii. Pass the string through the pulley at the end of the track and hang the mass support from that end.

6.2.2. Experimental procedure

i. The radius of the pulley used is $r = \underline{\ldots} \ cm$.

ii. The mass of the pulley used is $M = \underline{\ldots} \ g$. 
iii. Measure the mass of the mass support, this mass will be called $m_1$.

iv. Measure the mass of the cart with the washers, this mass will be called $m_2$.

v. For each of the data collection determine the total mass of the system, consider the masses $m_1$, $m_2$, and $M$. 

vi. Position the cart on the opposite end of the pulley, make sure that the mass support is suspended in the air and has a considerable distance to the ground.

vii. To carry out the data collection, take the control box and follow the following steps:

- Verify that the title "Newton's Second Law" appears on the screen.
- Press the "SELECT" key to continue with the experiment, "Release the carriage" will appear on the screen and prevent the carriage from colliding with the data pulley. Take the control box and follow the steps below:
  - Once the movement is finished, "t1 = xxxx" will appear on the screen, use the "UP" and "DOWN" keys to scroll through the 16 different times associated with the interaction of the pulley with the sensor.

viii. Press the "RESET" key to repeat the procedure.

ix. Repeat the above procedure for at least 4 different masses.

x. Determine the angular variation for each of the times obtained, for this, bear in mind that:

$$\theta_i = \frac{2\pi i}{10}$$

where $i = 1, 2, 3, ..., 16$.

xi. With the data obtained in the previous numerals, make a table containing the angles (in radians) related to each of the time measurements (in seconds).

6.2.3. Analysis

i. Make a graph of the angle in radians as a function of time for each of the assemblies. Describe what the behavior of the graph is. Indicate that you can conclude from this behavior. If in the previous numeral the graph obtained was not a straight line, perform a polynomial regression. What can you conclude from the results obtained? What physical meaning does this behavior have?

7. Conclusions

Finally, it is worth highlighting the importance of the development of prototypes for the experimental demonstration of fundamental physical laws, such as in this case Newton's Second Law, the developed prototype allows the hand of its guide, to experimentally verify the value of the acceleration of fall free. [6]

Likewise, it is possible to show that a large budget is not necessary for the development of projects such as the one shown in the article, where with a basic budget and the knowledge acquired in the academy, it is possible to contribute to the teaching of physics, which of one way or another impacts the interest of the current generation and encourages a taste for knowledge of basic sciences.

It is important to highlight that the DICOPED research group works continuously in the development of demonstration prototypes, strengthening the study of physics every day. Not only in the field of classical mechanics, if not in fields such as electricity and slightly more complex physical phenomena such as waves and light.

Recognitions

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References
[1] ANDALUSIAN SOCIETY OF MATHEMATICAL EDUCATION. Newton's Laws [online]. Available on the Web: http://thales.cica.es/rd/Recursos/rd98/Fisica/02/leyes.html

[2] LANDAU & LIFSHITZ. Mechanics. Ed. Reverté, Barcelona, 1991. ISBN 84-291-4081-6

[3] BOLIVARIAN REPUBLIC OF VENEZUELA, MINISTRY OF POPULAR POWER FOR HIGHER EDUCATION. Newton's Second Law of Rigid Body Dynamics [online]. Available on the Web: http://nestormorenodr.blogspot.com.co/p/13-segunda-ley-de-newton-de-la-dinamica.html

[4] ESPINOSA CARD, Rubén Darío. ANALOG ELECTRONIC DESIGN. Manizales, 2009. 226 pp.

[5] ANDALUSIAN SOCIETY OF MATHEMATICAL EDUCATION. Newton's Laws [online]. Available on the Web: http://thales.cica.es/rd/Recursos/rd98/Fisica/02/leyes.html

[6] Design and Construction of Prototypes for Physics Experiments I. Between Science and Engineering. ISSN 1909-8367. Year 5 No. 9. 210 Pages. From page 186 to 199.