

Development and construction of a didactic module of electrical circuits for remote experimentation through a web application and IoT resources

Desenvolvimento e construção de um módulo didático de circuitos elétricos para experimentação remota através de uma aplicação web e recursos de IoT

Desarrollo y construcción de un módulo didáctico de circuitos eléctricos para experimentación remota a través de una aplicación web y recursos IoT

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Abstract

This article presents the development and construction of a didactic kit of practical experiences of electrical circuits, remotely controllable through the internet, from low cost resources and devices, and easy to implement. Developed with open source technologies, the practice module was built from a Raspberry Pi, and subdivided into four parts: a web application (developed in Html, Css, Javascript, PHP and MySQL) and a local application coded in Python and runs on the Raspberry; two electronic boards, one for controlling the resistors of a circuit and the other as a variable power supply for the circuit; a cabinet designed and built in MDF to accommodate all the physical components of the equipment; and a mixed electrical circuit for experiments, consisting of 9 resistors, 10 voltmeters and 3 ammeters. To access remotely, a Login system was built, generating greater security and a button interface that, when triggered, make requests to a server, recording the status of the button pressed in an SQL Database (Structured Query Language). Tests were carried out to check the integrity of the hardware and software devices of the didactic kit, considering that they did not present any flaws, allowing the equipment to be installed in a physics laboratory, connected to the internet and made available intermittently for use by high school students.

Keywords: Internet of things; Mixed electrical circuit; Raspberry Pi; Remote practice.

Resumo

Este artigo apresenta o desenvolvimento e a construção de um kit didático de experiências práticas de circuitos elétricos, controlável remotamente através da internet, a partir de recursos e dispositivos de baixo custo, e de fácil implementação. Desenvolvido com tecnologias de código aberto, o módulo de práticas foi construído a partir de um Raspberry Pi, e subdividido em quatro partes: uma aplicação web (desenvolvida em Html, Css, Javascript, PHP e MySQL) e uma aplicação local codificada em Python e executada no Raspberry; duas

placas eletrônicas, uma de interface para controle dos resistores de um circuito e outra como uma fonte de alimentação variável do circuito; um gabinete projetado e construído em MDF para acomodar todos os componentes físicos do equipamento; e um circuito elétrico misto para experiências, composto por 9 resistores, 10 voltímetros e 3 amperímetros. Para acessar remotamente, foi construído um sistema de Login, gerando uma maior segurança e uma interface de botões que, ao serem acionados, realizam requisições a um servidor, registrando o status do botão acionado em um Banco de dados SQL (Linguagem de Consulta Estruturada). Foram feitos testes para verificar a integridade dos dispositivos de hardware e software do kit didático, tendo em vista que não apresentaram falhas, possibilitando ao equipamento ser instalado em um laboratório de física, conectado à internet e disponibilizado intermitentemente para ser utilizado por estudantes do ensino médio.

Palavras-chave: Circuito elétrico misto; Internet das coisas; Prática remota; Raspberry Pi.

Resumen

Este artículo presenta el desarrollo y construcción de un kit didáctico de experiencias prácticas de circuitos eléctricos, controlable remotamente a través de internet, a partir de recursos y dispositivos de bajo costo y de fácil implementación. Desarrollado con tecnologías de código abierto, el módulo de prácticas se construyó a partir de una Raspberry Pi y se subdividió en cuatro partes: una aplicación web (desarrollada en Html, Css, Javascript, PHP y MySQL) y una aplicación local codificada en Python y se ejecuta en la frambuesa; dos placas electrónicas, una para controlar las resistencias de un circuito y la otra como fuente de alimentación variable para el circuito; un gabinete diseñado y construido en MDF para acomodar todos los componentes físicos del equipo; y un circuito eléctrico mixto para experimentos, compuesto por 9 resistencias, 10 voltímetros y 3 amperímetros. Para acceder de forma remota, se construyó un sistema de Login, generando mayor seguridad y una interfaz de botones que, al ser disparados, realizan solicitudes a un servidor, registrando el estado del botón presionado en una Base de Datos SQL (Structured Query Language). Se realizaron pruebas para verificar la integridad de los dispositivos hardware y software del kit didáctico, considerando que no presentaban fallas, permitiendo que el equipo sea instalado en un laboratorio de física, conectado a internet y puesto a disposición de manera intermitente para su uso por estudiantes de secundaria.

Palabras clave: Circuito eléctrico mixto; Internet de las cosas; Práctica remota; Raspberry Pi.

1. Introduction

The use of practical experiments combined with technologies in the teaching of physics are extremely important for students' learning, and for this to exist, it is essential that the teacher has some tools to promote the student's interest in the studied subject, such as what will be developed in this project, the so-called virtual laboratories, being necessary so that the students get motivated during the classes (Tironi et al., 2013).

It becomes a great challenge for educators from all areas of knowledge to promote teaching practices so that the student has a meaningful learning of the subjects studied, and not learning in a mechanical way (Sim & Monteiro, 2018). Currently, we are in an extremely technological and globalized scenario, and we must use these points to our advantage, that is, combining technology with new teaching practices so that these students develop a meaningful learning of certain subjects treated in the classroom.

Several authors have shown through research the importance of experimentation for the teaching-learning process, knowing that there are numerous difficulties with the use of practical experimentation. The lack of resources and space to have a available laboratory are barriers found by several schools, mainly in high school, where this project will be applied (Tironi et al., 2013; Sim & Monteiro, 2018; Neves, Caballero & Moreira, 2006).

Remote experimentation would be a solution found to minimize or resolve these difficulties, since remote access can represent an easy way to provide interaction with real experiments and promote situations that provide meaningful learning about certain physics subjects taught in the classroom (Simão et al., 2013).

In physics teaching, Ohm's law and Kirchhoff's laws are extremely important tools for analyzing electrical circuits, being used for circuit analysis and applicable in numerous fields of study within electricity such as direct current electrical circuits, electrical circuits in alternating current, in the study of transients, analog electronic circuits, mathematical modeling, among many others (Boylestad, 2012).

Considering the choice of electrical circuits due to their relevance within physics and the difficulties that the learning of these topics represents for high school students, the use of didactic equipment with accessible and low-cost technologies becomes a great ally to increase the quality in physics education.

According to Evans (2011), Guarnieri (2010) & Sandeep et al. (2015), the increasing appearance of embedded technologies and the great availability of accessible computing platforms, countless low-cost options and easy commercial access appear as possibilities to be

used in development of machines and various products. We can find applications for remotely controlled devices over the internet, in engineering labs, as described in (Bermúdez-ortega et al., 2015). Thus, the choice of low-cost technologies that are often used in academic projects in accordance with Alkar & Buhur (2005), Anusha & Mahadevaswamy (2018), Kumar & Rajasekaran (2016) & Sonalis, Lagu & Sanjay (2014), allows for numerous advantages due to accessibility and the huge amount of information available in projects already developed.

This work aimed to present the development and construction of a didactic module for remote practices of electrical circuits, using IoT resources, enabling students, through a web interface, to perform real practical experiments remotely, through a low-cost hardware device programmed using free software.

2. Metodology

This work aimed to present the development and construction of a didactic module for remote practices of electrical circuits, using IoT resources, allowing students, through a web interface, to carry out real practical experiments at a distance, through a hardware device of low cost programmed in free software.

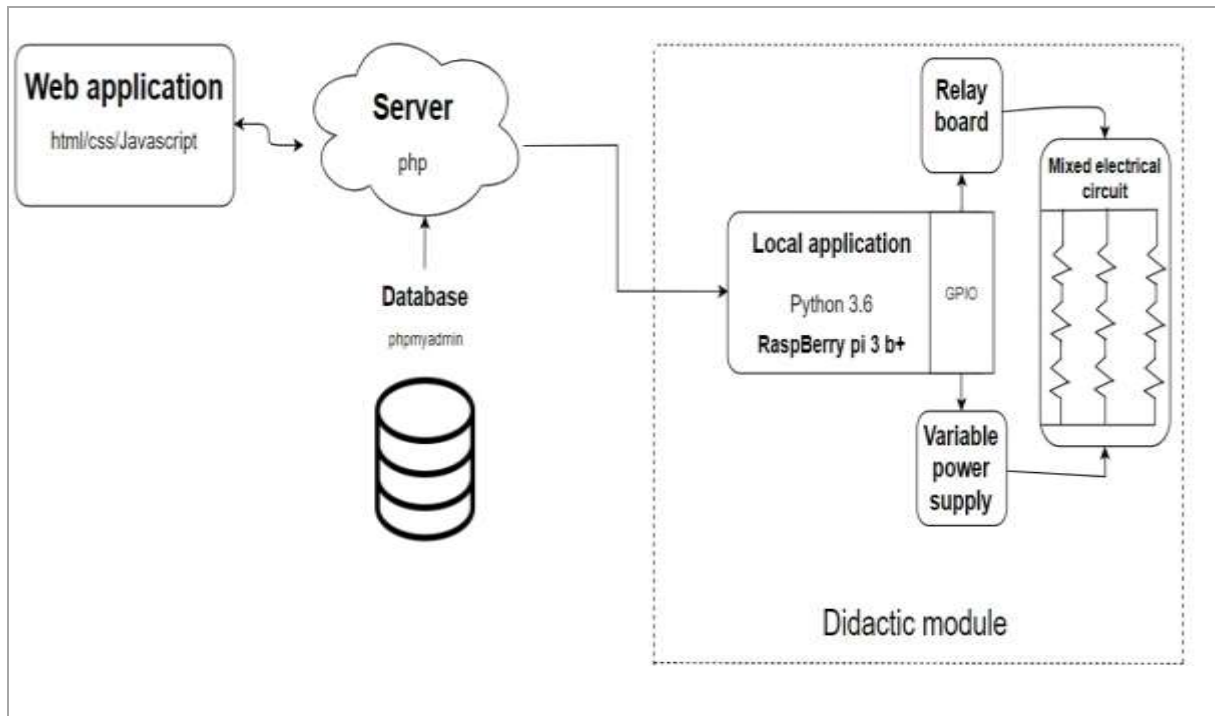
This type of research can be considered qualitative, since the results are evaluated according to the operation's success, analyzing the resources and functionalities of the developed equipment. All stages of development and construction of the proposed equipment were carried out in the university's electronic systems and applied physics laboratories. The final stages, which included tests of operation and use of the equipment, had the collaboration of teachers and high school students.

2.1 Overview of the proposed equipment

The design of the proposed teaching equipment can be divided into four main parts: the development of software for web and local application, the design and construction of electronic boards for powering and driving the circuit, the mechanical design and construction of the module cabinet and the development of the mixed electrical circuit.

Through the block diagram shown in Figure 1, we can verify that the system is composed of a web application, responsible for the control and monitoring of the electrical circuit components of the didactic module.

Figure 1. Block diagram of the proposed system.



Source: Authors (2020).

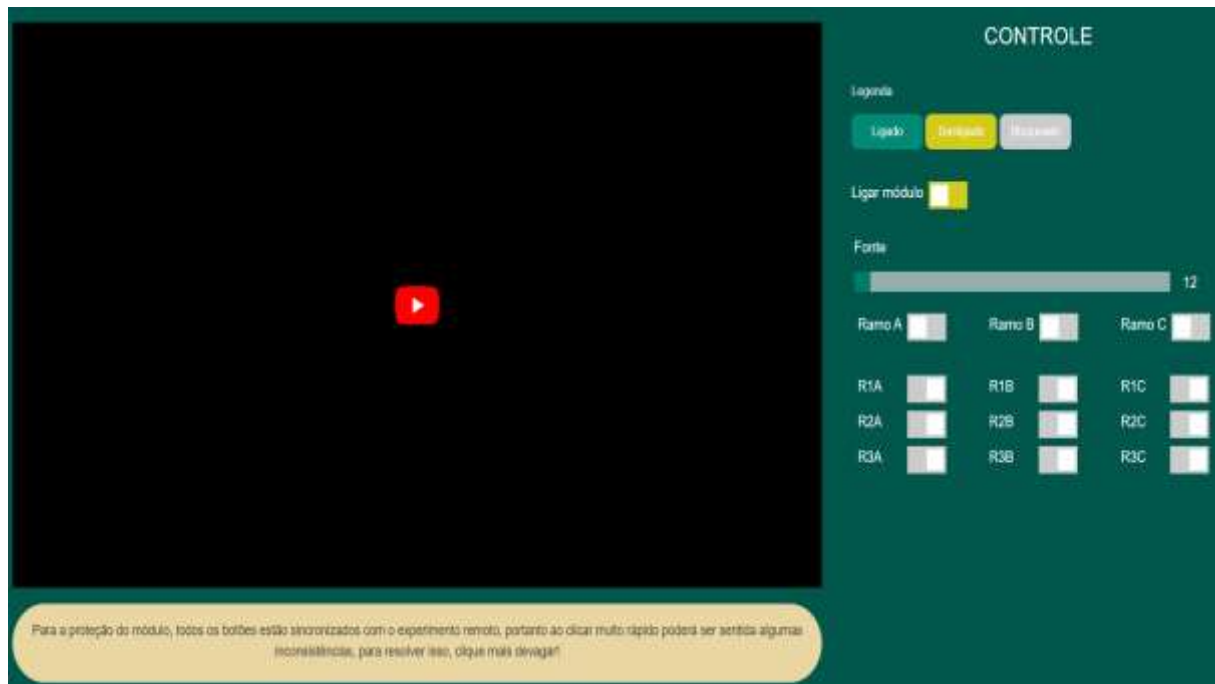
The webpage is managed by a user, remotely, through a graphical interface, using a local application to communicate with a database server and manage hardware devices. An on-board microcomputer is interconnected with two electronic boards. The block diagram includes the processes generated by the software and all hardware components connected to the processor (Figure 1).

2.2 Softwares development

A web application was built using PHP programming language as the back-end and JavaScript as the front-end language, with the aim of remotely controlling all the hardware resources of the didactic module.

As shown in Figure 2, the Web User Interface (WUI) consists of a set of buttons that enable the module during use, the individual control of the circuit branch and each resistor of the electrical circuit, and also through a horizontal bar selection, it is possible to adjust the value of the supply voltage of the circuit. The status of the controlled elements can be verified by changing the colors of the interface components.

Figure 2. WUI used to control devices remotely.



Source: Authors (2020).

The web application is hosted on a remote server, which allows an user to access via the internet. This application receives the status information from the relays sent by the user, and transmits them to a database, which is frequently consulted by the local application, developed in Python programming language and running an embedded computer system (Raspberry Pi).

The codes used in the construction of the web application and the local application were written in the Integrated Development Environment (IDE) Visual Studio Code which is open-source, developed by Microsoft. Different libraries were used for the development of each stage of the system.

The PHP back-end system was written using the SLIM microstructure (Micro Framework) that works in an APACHE environment. The front-end system was written in Javascript, using the JQuery library to make requests to the server and manipulate HTML visualized by the user.

A login system was developed for component security (Figure 3). The system uses the same technologies as the other parts of the module, except only the JWT (Json Web Token) technology. JWT is a secure token system for transmitting information, ensuring immutability, since there is a digital signature.

Figure 3. Web application UI - Access window.



Source: Authors (2020).

The user, when entering the login and password, will have his / her data encoded in base 64 and sent to the server, which decrypts them and compares the password with the HASH recorded safely in the database. If the login is correct, a JWT is created, containing basic information of the user, which is sent back to JAVASCRIPT, which stores it in the 'Local storage' of the browser, so that it can be accessed when necessary. If the user clicks 'logout', the browser will have the JWT deleted and the server will record that the JWT is no longer valid, which makes it safe so that there is no access fraud, if it has already been disconnected.

The Python application performs different functions, being responsible for reading the data from the server, checking the status of the electrical circuit elements of the didactic kit. Another function of the application is to provide a Local Graphical Interface (LGI), in order to present the status of the module elements, in order to monitor and detect possible failures when the equipment is used in person.

Such Python code will also make the current system data available via Raspberry Pi, and send the new data provided by the user to the electronic boards existing in the didactic module. Thus, the following libraries were used: Requests (Request to the server), Tkinter (Assembly of LGI), GPIO (Control of the outputs GPIO and PWM), among others non-essential. The commands for importing the modules are shown in Figure 4.

Figure 4. Codes for importing modules.

```
import tkinter as tk
import tkinter.font as tkFont
from PIL import ImageTk, Image
import ast

from RPi import GPIO
from time import sleep

import sys, os
import requests
import base64
import json
```

Source: Authors (2020).

The Python application was developed to receive the information sent by the user through the web application and transmit it to the electronic control boards of the electrical circuit of the didactic kit. This local application was developed to work inside a microcomputer, and the model chosen for this project was the Raspberry Pi 3 B +.

All applications are connected as follows: for each click made on the web user interface (Figure 2), JQuery sends a POST request to the PHP server informing the deactivation or activation of a button. Thus, PHP receives this information and writes a new record to the database (Figure 5), containing the status of all the buttons, including the button just clicked, and copying the values of the rest of the buttons.

Figure 5. Example of registration in the database.

inp_pk	inp_b_rele1	inp_b_rele2	inp_b_rele3	inp_b_rele4	inp_b_rele5	inp_b_rele6	inp_b_rele7	inp_b_rele8	inp_b_rele9	inp_b_rele10
101	0	1	0	0	0	0	0	0	0	0
102	1	1	0	0	0	0	0	0	0	0
103	1	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0
105	0	1	0	0	0	0	0	0	0	0
106	1	1	0	0	0	0	0	0	0	0
107	1	0	0	0	0	0	0	0	0	0
108	0	0	0	0	0	0	0	0	0	0
109	0	1	0	0	0	0	0	0	0	0
110	1	1	0	0	0	0	0	0	0	0
111	1	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0
113	0	1	0	0	0	0	0	0	0	0

Source: Authors (2020).

The Python application hosted on the Raspberry performs a GET request every 0.5 seconds, which receives the last record made in the database and compares it with the previous record. In case of any modification, a function related to the changed WUI button is executed, in addition to updating the Python LGI (Figure 6), showing the status of the didactic module's electrical circuit components.

Figure 6. Python's application - Local graphic interface.



Source: Authors (2020).

The Local Graphical Interface (Figure 6), offers the possibility to monitor the condition of each of the 13 relays that enable and disable the electrical circuit components. This graphic resource was developed to facilitate testing during the construction stages, and can be used as a support tool to track possible failures that may happen with the equipment.

2.3 Hardware resources and development

The Raspberry Pi (Figure 7) is a microcomputer that allows the installation of different operating systems (OS), consisting of 48 GPIO pins, SD card slot and 4 USB ports. All system hardware is connected to this processor, which operates with a 3.3V power supply.

The Raspberry Pi OS was chosen precisely for optimization with the hardware and for the variety of applications and pre-installed languages, including the Python language, which was used for the local system, which allows the system to be used in a generic way for all project types (Raspberry, 2019).

Figure 7. Microcomputer Raspberry Pi 3 B +.

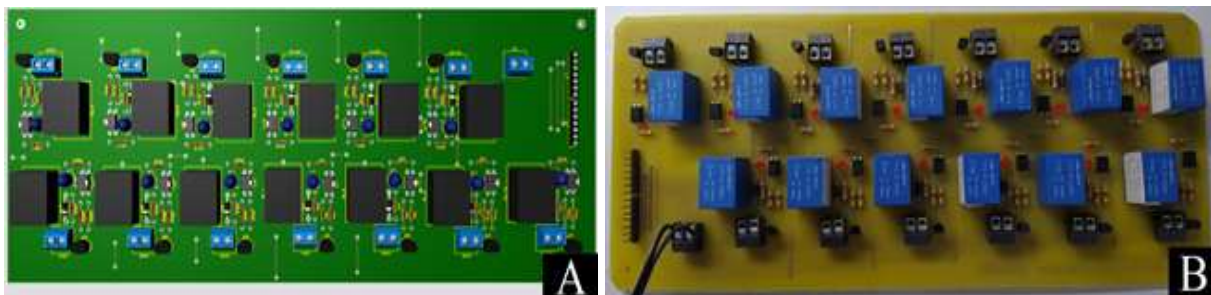


Source: Authors (2020).

Two electronic boards were built in order to act directly on the mixed electrical circuit (main element of the teaching equipment). A relay board (Figures 8A and 8B) was designed and manufactured to enable or disable branches and resistors of the mixed circuit. For this function, electromechanical relays connected in series and parallel with the resistors that make up the circuit of practical experiments were used.

The electronic relay board consisted of 13 energy-free contacts, each consists of a normally open (NO) and normally closed (NC) contact, combined in the same common terminal. The 3.3V signals provided by the Raspberry Pi GPIO are applied to opto-couplers on the board. The great advantage of an optical coupler is the electrical isolation between the circuits, in which the common point of one circuit is different from the common point of the other, being able to ground one of the circuits and leave the other in float (Bogart Jr., 2001), guaranteeing the electrical insulation between the microcomputer and the load firing plate. In Figure 8, the Printed Circuit Board (PCB) layout design in 3D and the electronic board, after being built, are presented.

Figure 8. Electromechanical relay board (A) 3D PCB Layout (B) Made board.



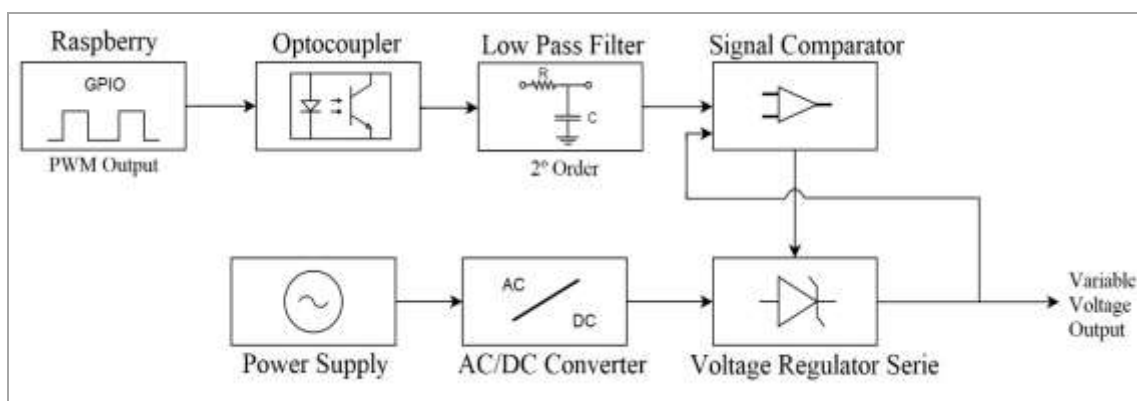
Source: Authors (2020).

The second electronic board is a linear type power supply with variable output, being developed and built with the intention of feeding the mixed electrical circuit, making its output voltage available according to adjustments made remotely through the web application.

To produce the variation of the source voltage, a digital output of GPIO, operating in Pulse Width Modulation mode (PWM) was used, enabling the variation of the voltage of a series-type regulator, present at the circuit output. We can see in more detail the main blocks (Figure 9) that make up the developed font. The power circuit consists of a bridge rectifier with capacitive filter and a transistor voltage regulator.

The PWM signal sent by the Raspberry GPIO activates an optical coupler, which performs the isolation between the circuits. A second-order Low Pass filter is applied to the signal, transforming the square wave signal into a continuous signal (Malvino and Bates, 2011).

Figure 9. Power Supply Block Diagram.

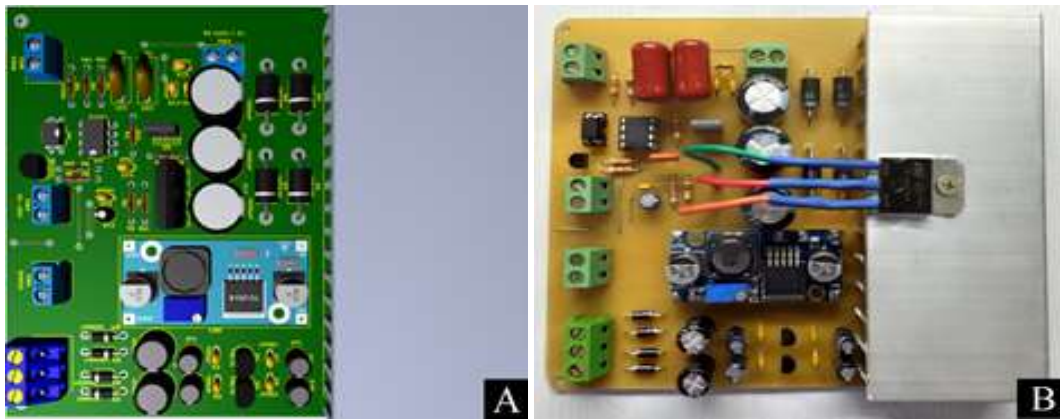


Source: Authors (2020).

A voltage comparator circuit with negative feedback is used to control the voltage drop in the series regulator, collecting a sample of the output signal to be compared with the control signal. The PWM signal has the function of defining the desired output voltage value (Set Point) by varying the output voltage according to the pulse width.

The design of the electronic boards was carried out in three stages: at first, the electronic circuits were elaborated and simulations of operation were carried out; in the second stage, the layouts of the printed circuit boards were developed (Figures 8A and 10A), and lastly, PCB were made for subsequent assembly of the components and tests (Figures 8B and 10B).

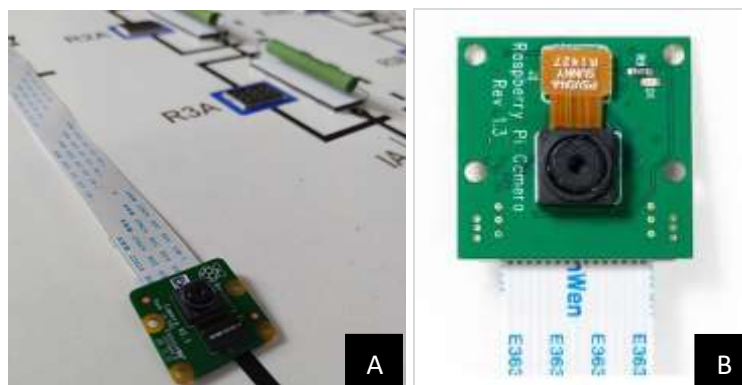
Figure 10. Variable power supply board (A) 3D PCB Layout (B) Made board.



Source: Authors (2020).

In order to capture the image of the didactic kit in real time, the camera module for Raspberry Pi was chosen, being a low cost solution, composed of a 5MP sensor, with dedicated connection through the SCI port (Serial Camera Interface), offering a resolution of up to 1080p30 for capturing videos (Figure 11).

Figure 11. Raspberry PI v 2.1 camera (A) being installed on the device (B) upper view.



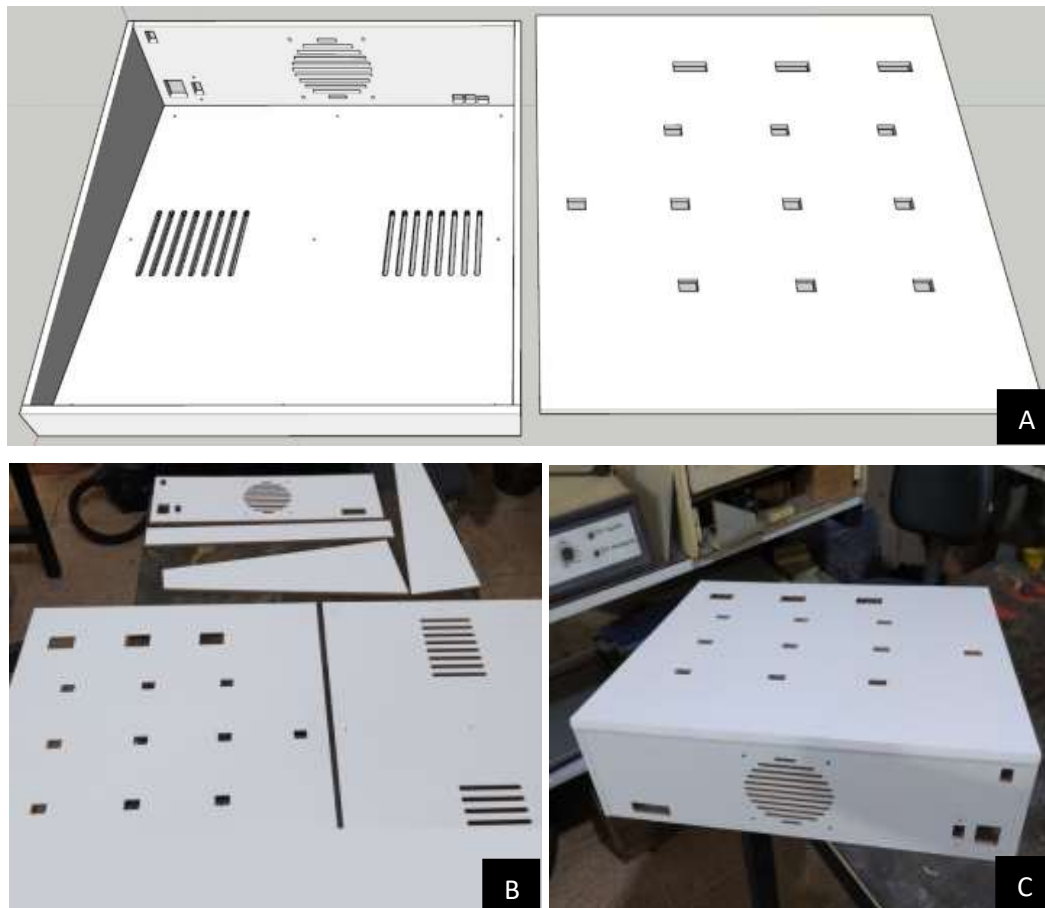
Source: Authors (2020).

The camera was installed on a support fixed directly to the module's box, allowing the position adjustment to capture the entire upper front of the equipment. Using a 1.5 meter long flat cable, it was possible to install the camera at a distance of approximately 1 meter above the teaching kit.

2.4 Mechanical design

In order to accommodate all the electronics components of the equipment, and to provide a front panel containing all the elements of the mixed electrical circuit, a 9 mm thick MDF plate cabinet was designed and built, all covered in white, measuring 500 mm in length, 550 mm wide, 160 mm rear height and 57 mm front height. For the manufacture of this cabinet, a CNC Router machine, model ASS3020, from the company Assimile Tecnologia was used, ensuring precision, speed and quality in the mechanical design. The 3D design and the case after being manufactured and assembled, can be seen in Figure 12.

Figure 12. MDF cabinet (A) 3D design (B) Pieces after cutting (C) Assembled cabinet.



Source: Authors (2020).

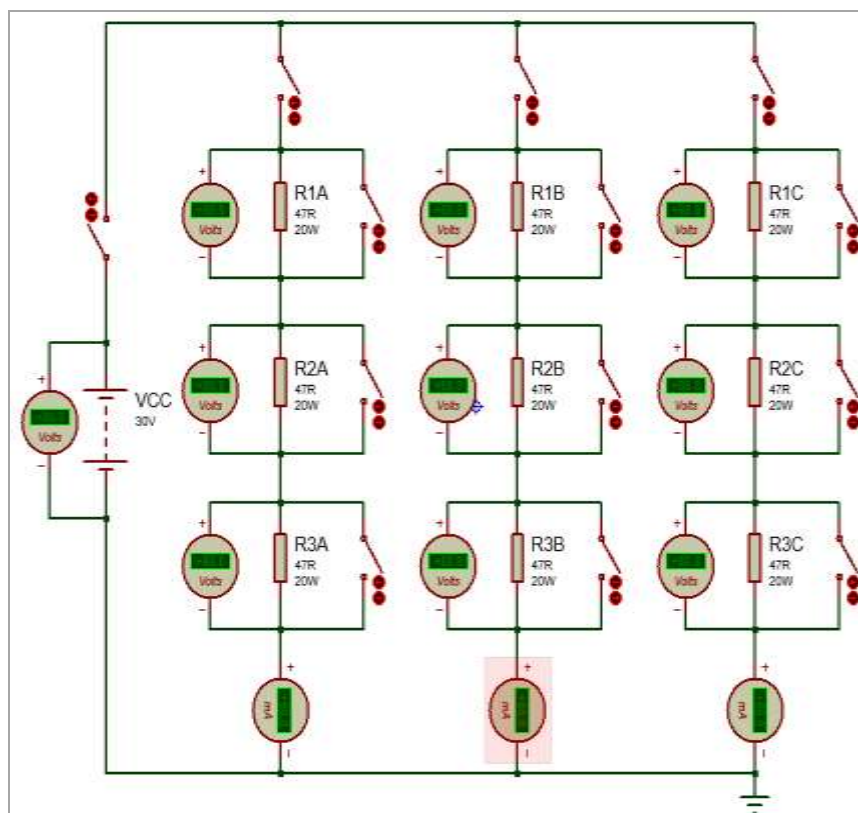
Cutouts were made on the top front of the case to accommodate digital voltmeters and ammeters, and on the back of the case, cuts were made to install a main switch (on / off), a power cable connector and a power selection switch. supply voltage (127 or 220VAC).

Still at the rear, a small rectangular access was created for external access to the communication ports of the Raspberry Pi (Network and USB). Air inlets and outlets were also built, positioned at the rear, with the possibility of attaching a cooler, and also at the bottom of the cabinet, providing two slots as air vents.

2.5 Mixed electrical circuit

The last stage of the project was the development of the mixed electrical circuit, the main element of the project, with the objective of offering practical experiments through circuits configured by the user at the end of the didactic equipment. A circuit with nine resistors associated in series and parallel was chosen, consisting of three branches associated in parallel and each containing three resistors in series, enabling the student to carry out practical activities with series, parallel and series-parallel circuits, also called a mixed circuit (Figure 13).

Figure 13. Mixed electrical circuit diagram.



Source: Authors (2020).

The resistors used in the circuit were made of wire with a porcelain wrapper, with a maximum power of 20W, tolerance of 20% and resistance of 47ohms. The variable power supply (Figure 10), supplies power to the circuit and allows a voltage adjustment from 12V to 30V, adopting this minimum voltage range to ensure that the voltmeters remain on, even in the condition where the user enables the three resistors from a single branch, considering that the voltmeters were connected in parallel with each resistor, and each voltmeter needs at least 4V to supply its control circuit. Likewise, a maximum limit of 30V was established, in order to establish higher current values and guarantee a safety voltage level (extra low voltage).

The maximum current limit of the circuit was defined considering that the conditions of current variation should not exceed the limits of the equipment. For this circuit, the highest current values were defined in the condition that the circuit has only one resistor enabled per branch, and the three branches enabled, resulting in a value of approximately 600mA per branch, totaling 1.8A drained from the power supply. The power supply was designed to supply up to 3A, allowing a safe current range of the equipment, for any circuit configuration.

3. Results and Discussion

Functional tests were performed, integrating the Web application with the database that is present on the server, through requests made to the back-end, with varying values, to make sure that the communication had no error. Tests were also carried out about the communicating with the local RaspBerry Pi application, through the same requests to the server's "endpoints", that is, to the links generated by the server to perform functions in the database. Both tests proved the effectiveness of the communication between the server and the applications, reaching the initial objectives.

Considering that the user of the equipment is free to enable and disable branches and resistors in different ways, and that the resistors are disabled by short circuits produced by the relays connected in parallel, unsafe conditions that could result in the malfunction of the circuit would be possible. In this way, some interlocking operations were performed, that is, protection barriers, through the codes, which would not allow the user to carry out operations that could cause damage to the module. Thus, barriers were created in the Javascript code, in the server-side with the PHP language, and in the local application coded in Python. The interlocking barriers proved to be effective, as was seen in the tests performed.

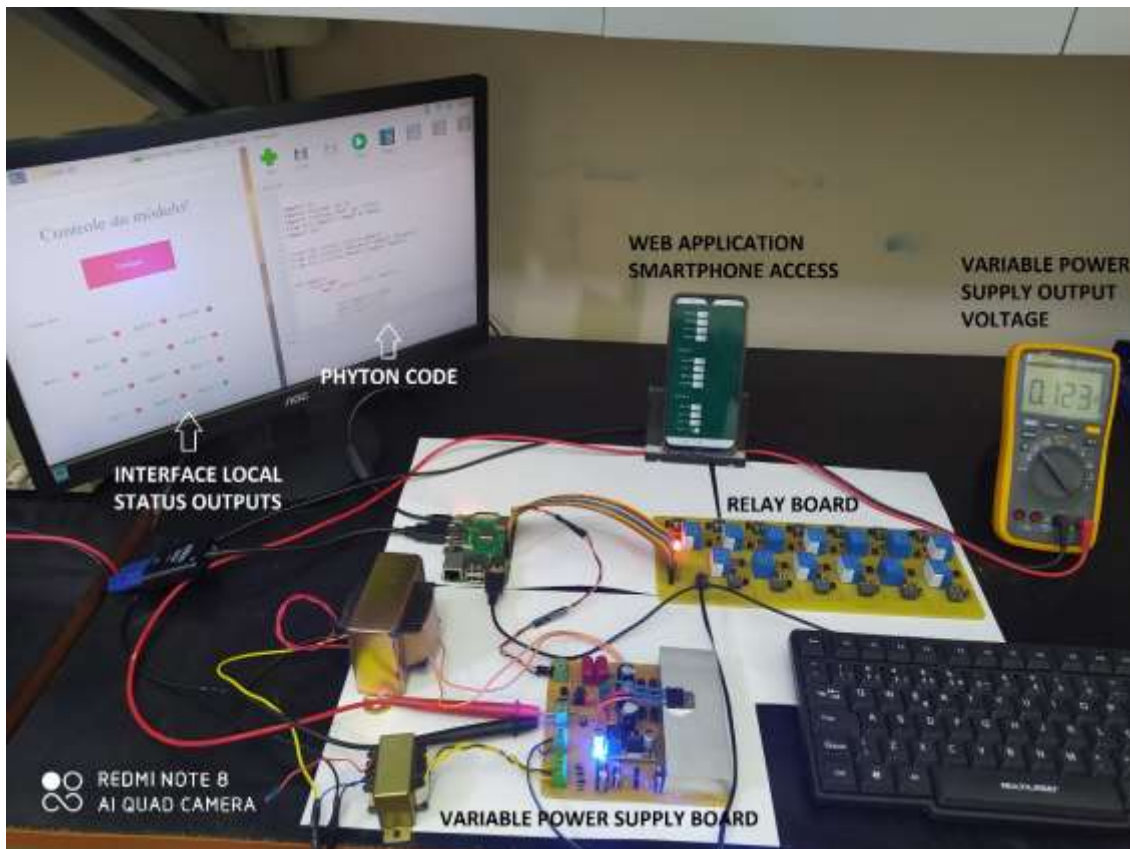
The local application has the function of writing values in GPIO and, for that, it was also tested. A digital multimeter was used to check the voltage values of the RaspBerry Pi

digital outputs and the tests showed the values we expected. In this case, we used the library named GPIO, open-source, available for import in Python and with support from Raspberry.

After the code was published on the server, the last tests were made, which consisted of accessing the web application from a computer and observing changes in the module due to the activation done online, making it possible to state that the test was effective, having all the software in operation as planned.

In Figure 14, we can see a part of the components used in the didactic kit. To ensure the integration of hardware and software, bench tests were initially carried out, tracking all stages of the process, from the web application to the activation and alteration of the physical boards.

Figure 14. Hardware assembly and WUI testing.



Source: Authors (2020).

After the development, construction, assembly of the didactic module and communication tests were completed, the entire set of module components was energized, with the whole set already assembled in the cabinet, with the intention of ensuring that all power connections and those between components were correct.

From the physical tests we can highlight the connections between the Raspberry's GPIO pins and the relay board, including the measurement and adjustments of the PWM signal. The operating voltage limits of the source and the heating of components such as circuit resistors and the transformer, were also checked and monitored during operating conditions. In Figure 15, we can see the equipment submitted to this second test stage.

Figure 15. Testing of components (A) GPIO and PWM measurements (B) Open cabinet.

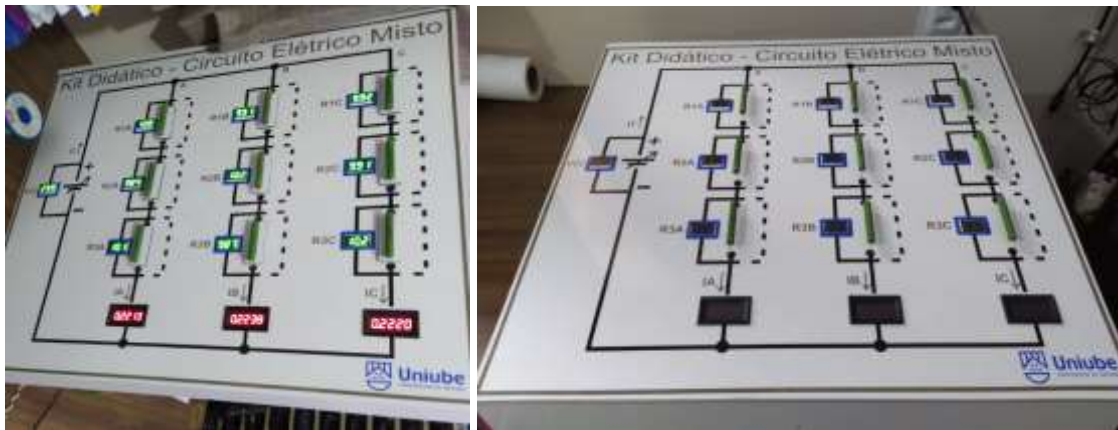


Source: Authors (2020).

In its upper external part of the module (Figure 16B), a schematic representing the main electrical circuit was created, featuring 9 resistors of 47 ohms, 10 voltmeters and 3 ammeters, which can be viewed and interacted via the web, through the graphical user interface. The indication of the enabling of the resistors is carried out by visual indication of the voltmeters and the enabling of the branches of the circuit indicated by the energization of the ammeters.

After all the physical and logical tests performed, all components were positioned and fixed inside the cabinet and the module was energized for successive use operations. The energized equipment, with all resistors enabled, can be seen in Figure 16.

Figure 16. Equipment ready for functional tests.



Source: Authors (2020).

The availability of a video in real time for the user was made through the YouTube platform, with a camera attached to the Raspberry Pi and started from a command line on the microcomputer's terminal. The process begins with the creation and configuration of a live broadcast on the YouTube channel created especially for the module. The platform provides an access code and the transmission server, so, later, this data is added to the command that will be executed.

The executed code performs two functions: initializing the camera and transmitting it to the selected server. The configuration was made in a way that, when starting the Raspberry Pi, two scripts are executed, one script that initializes the physical module and another that starts the live transmission. Thus, under normal conditions, human intervention is not necessary for a configuration of the Raspberry each time it is turned on, even though this access is possible by remote access software. Figure 17 shows the didactic kit of electrical circuits being used and controlled remotely. The camera image is shown on the local monitor connected to the raspberry Pi.

Figure 17. Equipment being used and controlled remotely.



Source: Authors (2020).

As a final step in this project, the equipment was installed at the UNIUBE Physics Laboratory, connected to the internet and made available intermittently for use by high school physics students. The main objective of this work was successfully achieved, in which the expected equipment features had perfect functionality.

In this last stage, two high school students from the Colégio Nossa Senhora das Dores, located in the city of Uberaba, Minas Gerais, were invited to test the functionality of the equipment. Through the WUI, the students remotely performed various circuit assemblies on the module, checking the values of the electrical quantities of the circuit using voltmeters and ammeters, and comparing with calculated values the voltage drop caused by each resistor and the electric current of each branch, being it is possible to verify through practical experiment the first Ohm's Law and Kirchhoff's Laws for currents and voltages.

As a proposal for the continuity of this work and in order to measure the effectiveness of the application of didactic equipment in the teaching of physics, other works will be carried out using tools of comparison and measurement learning, and also considering the development of practice scripts with orientations and instructions for each student.

4. Conclusion

It was possible to develop and build the mixed electrical circuits didactic kit to develop practical activities remotely in high school students. The equipment proved to be extremely functional, making it possible to be monitored and controlled remotely, through an interactive web user interface, and allowing the accessibility of any student who has a computer or smartphone and an internet link to connect to it.

This article can demonstrate the construction and application of a low-cost device, with accessible technologies and easy to be developed, which can be easily accessed by any device. All software resources and Raspberry Pi equipment can be used for the development of more sophisticated teaching equipment, with this work as a reference for the development of others, which involve automation and IoT.

The possibility of continuing this research in future works may measure through quantitative analysis, the effectiveness of using the didactic module, being applied continuously in the teaching of physics, thus, measuring the direct contributions to the students' significant learning.

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