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ORIGINAL

Design and Implementation of a Didactic Monopolar Electrosurgical Simulator for Biomedical Engineering Education

Diseño e implementación de un simulador didáctico de electrobisturí monopolar para la enseñanza en ingeniería biomédica

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ABSTRACT

This work presents the development of a didactic monopolar electrosurgical unit (ESU) simulator, designed as a support tool for the technical training in the handling and basic operation of this medical device within academic environments. The simulator aims to facilitate both theoretical understanding and practical experience of the electrosurgical unit's operating principles, allowing students to interact with a functional system that replicates its primary modes: cutting and coagulation. The system architecture is based on an ESP32 microcontroller, which generates PWM signals within an adjustable range of 200 kHz to 1 MHz, controlled via rotary encoder potentiometers, and displayed in real time through an LCD screen with I2C interface. The power stage integrates an IRFZ44N MOSFET and a high-frequency transformer, configured to maintain energy levels within safe limits. The activation circuit incorporates 4N25 optocouplers, ensuring electrical isolation between user controls and the power electronics. This simulator is conceived as a formative platform capable of replicating realistic operational scenarios, promoting safe, scalable, and practical learning—particularly suited for biomedical engineering education and related disciplines.

Keywords: Didactic Simulator; Monopolar Electrosurgical Unit; Biomedical Engineering; ESP32; Technical Training.

RESUMEN

Este trabajo presenta el desarrollo de un simulador didáctico de electrobisturí monopolar, concebido como una herramienta de apoyo para la enseñanza técnica del manejo y funcionamiento básico de este equipo médico en contextos académicos. El simulador busca facilitar la comprensión teórica y práctica del principio operativo del electrobisturí, permitiendo la interacción del estudiante con un sistema funcional que reproduce sus principales modos de operación: corte y coagulación. La arquitectura del sistema se basa en el uso de un microcontrolador ESP32, encargado de generar señales PWM dentro de un rango ajustable de 200 kHz a 1 MHz, reguladas mediante potenciómetros con encoder, y presentadas en tiempo real a través de una pantalla LCD con interfaz I2C. La etapa de potencia incorpora un MOSFET IRFZ44N y un transformador de alta frecuencia, configurados para mantener niveles seguros de energía. Por su parte, el circuito de activación utiliza optoacopladores 4N25, los cuales garantizan el aislamiento entre los controles del usuario y la electrónica de potencia. El simulador está diseñado como una plataforma formativa que permite replicar escenarios de operación reales, promoviendo un aprendizaje práctico, seguro y escalable, ideal para entornos de formación en ingeniería biomédica y disciplinas afines.

Palabras clave: Simulador Didáctico; Electrobisturí Monopolar; Ingeniería Biomédica; ESP32; Formación Técnica.

INTRODUCTION

The electrosurgical scalpel is widely used in modern surgery due to its ability to perform precise cuts and tissue coagulation using high-frequency electric current, minimizing bleeding and reducing surgical time.[1] Its operating principle is based on converting electrical energy into localized heat, which allows tissue intervention without direct mechanical contact.[2] This equipment represents a fundamental tool in different medical specialties, from general surgery to dermatology and gynecology.

Despite its clinical relevance, access to electrosurgical scalpel equipment for educational purposes is limited, especially in technical training institutions or developing countries, due to its misuse's high cost, operational complexity, and risks.[3] This creates a significant gap between the theoretical knowledge and practical experience of biomedical engineering students, who need to understand both the principle of operation and the safety and technical handling aspects of the equipment.

In response to this problem, several studies have proposed using didactic simulators to replicate the operation of complex medical devices in a controlled and safe environment.[4] However, most available developments focus on diagnostic simulators, leaving aside high-frequency surgical equipment like the electrosurgical scalpel.

Therefore, the present work aims to design and implement a didactic monopolar electrosurgical scalpel simulator oriented to the practical teaching of the technical handling of this equipment in academic environments. The simulator seeks to replicate the basic functions of cutting and coagulation, integrating accessible technologies such as microcontrollers, power electronic components, and a graphical interface to enhance the learning experience and reinforce the theoretical contents through guided practice.

METHOD

The didactic monopolar electrosurgical simulator was designed and developed using a modular structure divided into three main blocks: control system, activation system, and power stage. All stages were developed using commercially available components and open-source technologies to ensure the prototype's reproducibility in academic environments.

Control system

An ESP32 DevKit v1 microcontroller was programmed for the system's core using the Arduino IDE development environment. This device generated PWM signals to simulate the cutting and coagulation modes and managed the user interface. The PWM signals were frequency modulated, ranging from 200 kHz to 1 MHz, and their duty cycle was adjusted using rotary encoders with pushbuttons connected to the microcontroller's GPIO inputs.

The parameters (frequency and simulated power) were displayed on a 16x2 LCD display with an I2C interface, controlled from the ESP32. The power supply for this section was an external 5 V / 5 A power supply, electrically isolated from the rest of the system.

Figure 1 shows the circuit made for the prototype control system.

Triggering stage

The activation of the operating modes (cutting and coagulation) was implemented using 4N25 optocouplers to guarantee galvanic isolation between the control logic and the power stage. A commercial electrosurgical pencil was used for activation, taking advantage of its original activation buttons. The push-button momentary contact switches integrated into the pencil were connected to the optocouplers, which activated the PWM outputs using discrete signals detected by the ESP32.

Figure 2 shows the circuit realized for the activation stage of the prototype.

Power stage

The power stage was designed to simulate the actual operation of the electrosurgical unit without reaching dangerous levels. For this purpose, an IRFZ44N MOSFET transistor, configured as a high-speed switch, was used to switch a high-frequency ferrite core transformer specifically designed to amplify the signal generated by the PWM. The output power was intentionally limited to a maximum of 0,4 A to ensure the equipment was safe for educational use.

The transformer was designed using principles described in technical literature.[5] It was mounted on an acrylic base with a passive heatsink to avoid overheating.

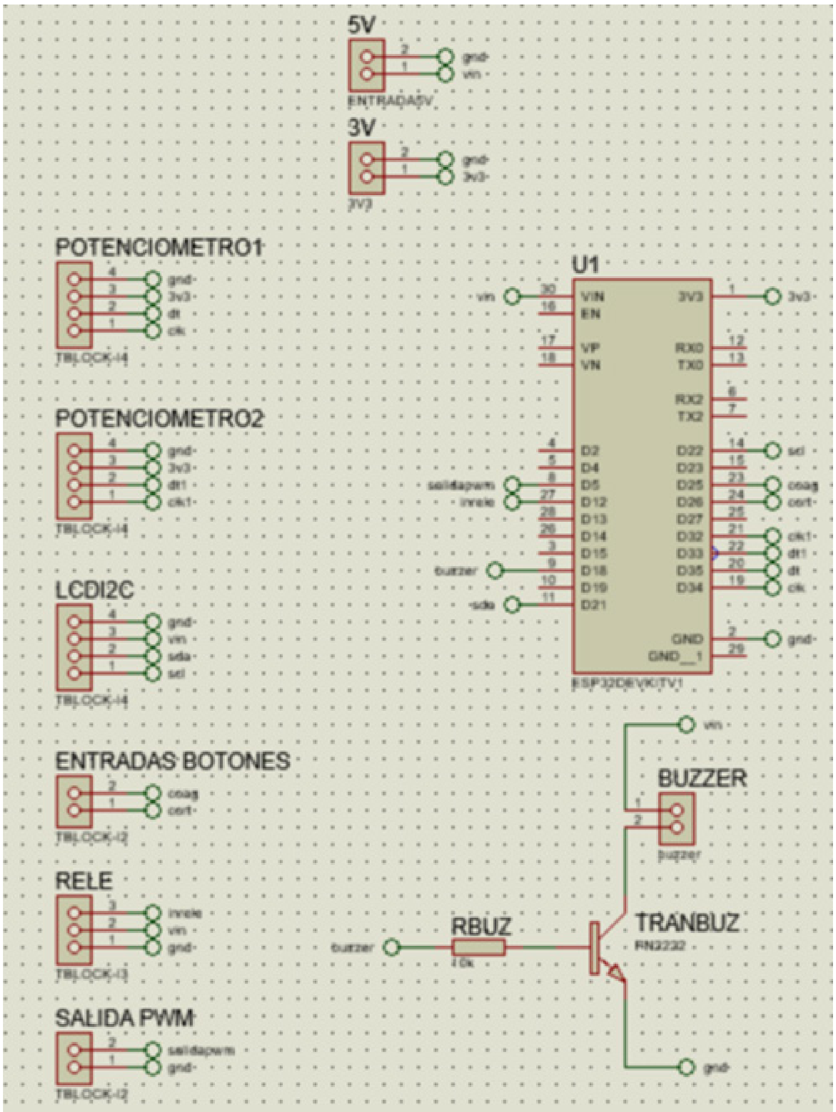

Figure 1. Design of a didactic electrosurgical unit for the training of biomedical engineering students

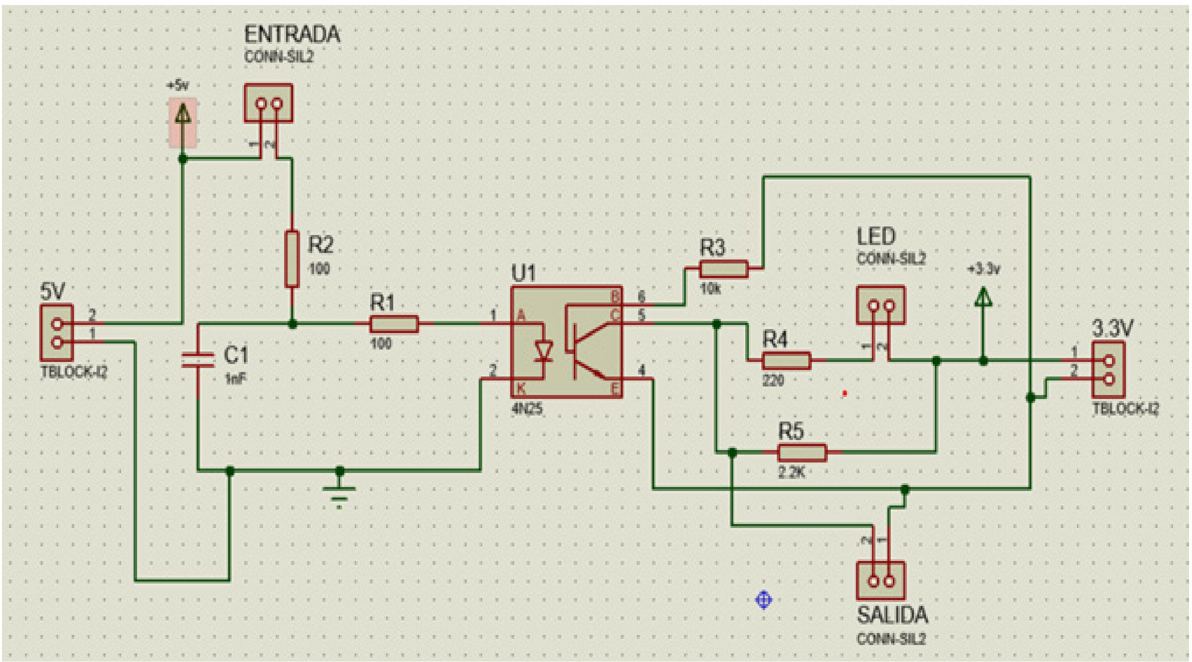

Figure 2. Design of a didactic electrosurgical unit for the training of biomedical engineering students

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Figure 3 shows the circuit made for the power stage of the prototype.

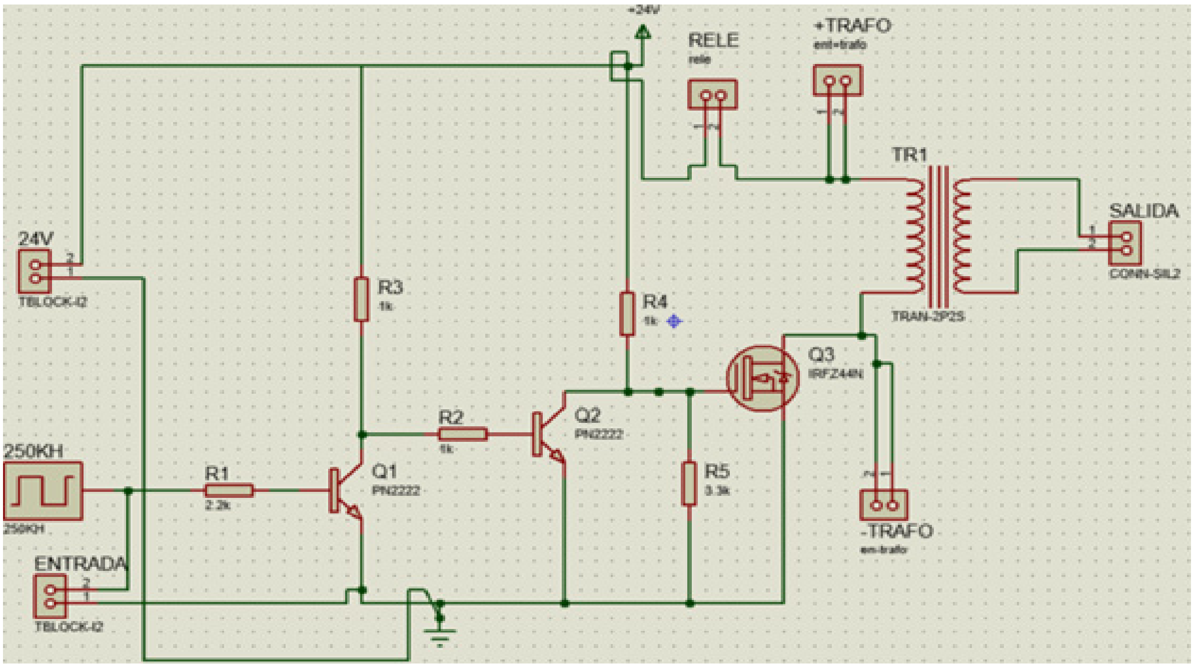

Figure 3. Design of a didactic electrosurgical unit for the training of biomedical engineering students

Web interface

A graphical interface was developed using HTML, CSS, and JavaScript, hosted locally on the ESP32 via an embedded server. This interface allowed for managing user access, defining groups of students, controlling access to the learning stages (theory, test, practice, and evaluation), and visualizing the simulator's status in real time.

Functional validation

The prototype was tested under real conditions of educational use. Electrical safety measurements were performed using Fluke ESA620 equipment,[6] which allowed verification of the values of earth resistance, leakage current to the case, and line-to-line voltage. Subsequently, the equipment was presented to two medical professionals (one from the dermatological area and the other from the internal medicine area), who carried out a functional evaluation of the simulator. Finally, the system was used by a group of 21 final-semester Biomedical Engineering students, selected voluntarily, who completed the proposed interaction stages.

RESULTS

The monopolar electrosurgical scalpel didactic simulator was developed according to the proposed modular structure, which integrates the three main blocks: control system, activation stage, and power stage.

Control system

The control system based on an ESP32 DevKit v1 microcontroller was successfully implemented. The device generated frequency-modulated PWM signals within the set range of 200 kHz to 1 MHz, and the duty cycle was adjusted by means of rotary encoders. The 16x2 LCD with an I2C interface showed the simulated frequency and power values in real time, allowing clear and accessible interaction for the user. Figure 1 shows the circuit developed for this section of the prototype, evidencing the connection of the microcontroller with the input and output components.

Activation stage

The cut-off and coagulation modes were activated using 4N25 optocouplers, guaranteeing the required galvanic isolation. The push buttons integrated into the handle responded correctly to the system signals, allowing the activation and deactivation of the PWM signals. The activation circuit is presented in figure 2, which details the connection between the switches, optocouplers, and the microcontroller.

Power stage

The power stage used an IRFZ44N MOSFET transistor configured as a fast switch, which drove a ferrite core transformer designed to amplify the generated PWM signal. The output current was limited to a maximum of 0,4 A, ensuring safety during educational use.

Mounting the transformer on an acrylic base with a passive heatsink prevented overheating during operation. The corresponding circuit is shown in figure 3.

Web interface

A graphical interface was developed and hosted locally on the ESP32. This interface allowed user management, access control to the learning stages, and real-time visualization of the simulator's status. This interface facilitated the interaction between students and the prototype during the practical exercises.

Functional validation

The prototype was tested for electrical safety with Fluke ESA620 equipment, verifying that the values of earth resistance, leakage current, and line-to-line voltages were within safe parameters for didactic use.

Two medical professionals evaluated the simulator, which met the functional expectations for learning how to operate the electrosurgical unit. Finally, the 21 volunteer students satisfactorily completed the proposed interaction stages, corroborating the prototype's functionality and usability.

DISCUSSION

The development and validation of the monopolar didactic electrosurgical scalpel prototype represented a significant advance in improving the teaching-learning process for students in the health areas who need to understand and manipulate this equipment. The results show that the system's modular structure, based on commercial components and open technologies, facilitates not only the reproduction of the prototype in academic environments but also its adaptation to different training scenarios.

Implementing the ESP32 microcontroller for generating and controlling PWM signals made it possible to simulate with sufficient fidelity the real operating modes of the electrosurgical unit, a fundamental aspect for students to safely and practically experience the basic principles without electrical risks. These findings align with previous studies highlighting the importance of using configurable and modular electronic systems for teaching devices in biomedical engineering.

The activation stage, with galvanic isolation by means of optocouplers, ensured the system's safety and robustness, evidencing a careful design that avoided interference between the control logic and the power stage. The inclusion of the surgical pencil contributes to a more immersive and realistic experience for the user, favoring kinaesthetic learning, an aspect little explored in previous simulators.

On the other hand, the power stage was limited to 0,4 A, and using a passive heatsink prevented any risk of overheating or damage, maintaining the indispensable safety of educational equipment. This approach of intentional power limitation is congruent with recommendations for educational prototypes that seek to reproduce the behavior without the risks inherent in real clinical equipment.

The developed web interface allows for managing users and learning stages, integrating theory and practice in a single system. This not only improves accessibility but also enhances interaction and pedagogical follow-up, aligning with current trends in health technology education.

During the functional validation, although the evaluation by professionals and students was positive, some potential limitations were identified, such as the need for periodic calibrations of the PWM system to maintain the fidelity of the simulation, which should be considered for future versions. Furthermore, no significant anomalous results were presented, indicating an adequate robustness of the prototype for educational purposes.

CONCLUSIONS

The present research achieved the design and implementation of a didactic simulator of monopolar electrosurgical scalpel oriented to teaching in health careers, particularly in Biomedical Engineering, allowing the practical and safe understanding of the operation of this medical equipment of frequent clinical use.[7] The development of the prototype was based on a modular, low-cost, and easy-to-reproduce architecture using open-source technologies and commercially available components.[8] This strategy facilitated its implementation in academic contexts and ensured the functionality of each subsystem in isolation and together.

Based on an ESP32 microcontroller, the control system allowed PWM signals to be generated with modulated frequencies between 200 kHz and 1 MHz, accurately simulating shear and coagulation modes. The activation stage, with galvanic isolation using 4N25 optocouplers, integrated a commercial electrosurgical pencil, respecting the experience of clinical use. The power stage was operated by an IRFZ44N MOSFET and a ferrite transformer, limiting the output current to a maximum of 0,4 A to ensure user safety. The system was mounted on an acrylic base with passive heat dissipation, preventing overheating.

During validation testing, the prototype was evaluated with a Fluke ESA620 biomedical test set, obtaining satisfactory results in 100 % of ground resistance, leakage current, and line-to-line voltage measurements,

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demonstrating that the simulator meets basic electrical safety standards for educational use. In the end-user testing stage, the simulator was subjected to a practical experience with 21 final semester Biomedical Engineering students, selected voluntarily. Ninety-five percent of the participants reported a clearer understanding of the operation of the electrosurgical scalpel compared to conventional lectures, and 90 % said that the simulator allowed them to become familiar with its safe handling.

From the author's point of view, this type of tool represents a significant contribution to academic training in environments where access to real clinical equipment is limited or risky. In addition, it promotes an active education focused on experimentation and self-management of technical knowledge by the student. In this sense, the simulator fulfills its pedagogical function and promotes the development of practical skills essential for safe, professional practice.

Finally, the integration of haptic feedback technologies to simulate tissue response, incorporating sensors to record usage data and user errors, and developing an automated performance evaluation module are recommended as future lines of work. These improvements will allow the simulator to evolve towards a more immersive, measurable, and adaptable training environment for different levels of education, strengthening future healthcare professionals' clinical and technical training.

REFERENCES

1. González M, Pérez L, Ortega F. Aplicaciones clínicas del electrobisturí en cirugía general. Revista Latinoamericana de Tecnología Médica. 2021;18(2):115-123.

2. López R, Ramírez D. Principios físicos y operación segura del electrobisturí. Revista de Ciencias Biomédicas. 2019;11(1):33-40.

3. Vallejos C, Méndez A. Limitaciones en la formación práctica en ingeniería biomédica: Un análisis desde la perspectiva latinoamericana. Educación en Ingeniería y Tecnología. 2020;5(3):55-63.

4. Martínez J, Herrera P, Quispe M. Diseño de simuladores para la enseñanza de dispositivos médicos en educación superior. Avances en Ingeniería Biomédica. 2018;6(1):20-28.

5. Boylestad RL, Nashelsky L. Fundamentals of electronics. 11th ed. Pearson; 2017.

6. Fluke Corporation. Guía de uso del Fluke Biomedical ESA620. 2022. Available from: https://www.fluke.com/manuales/esa620

7. Garcés JE, Villalobos HA. Simuladores didácticos como herramientas para el aprendizaje activo en ingeniería. Revista Educación en Ingeniería. 2018;13(25):59-66. doi:10.26507/rei.v13n25.763

8. Hakanen JJ, Luoto L. Open source hardware in engineering education: Case of Arduino. IEEE Global Engineering Education Conference. 2012:1-5. doi:10.1109/EDUCON.2012.6201053

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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