HAPTIC SURGICAL SCALPEL WITH BLE COMMUNICATION INTEGRATED INTO IMMERSIVE VIRTUAL REALITY ENVIRONMENT

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ABSTRACT

This article presents the technical report on the development of a haptic surgical scalpel with Bluetooth Low Energy (BLE) communication, designed for integration into immersive virtual reality (VR) environments using the Meta Quest 2 headset. The device, based on the Seeed XIAO BLE Sense nRF52840 microcontroller, integrates motion sensors, vibration motors and a manual control interface. BLE communication allows real-time transmission of motion data and commands to the virtual environment, where they are interpreted and used for interactive surgical simulations. Tests have shown low communication latency (~22 ms), high sensory accuracy and stability of data transmission, as well as a battery life of up to 10 hours. The implemented haptic feedback system allowed sensory differentiation between simulated layers of skin, muscle and bone. The results point to the potential of the device as a tool to support medical training and immersive teaching technologies.

Keywords: Haptic Feedback. Surgical simulation. Medical Device. BLE. 3DUI.

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INTRODUCTION

Virtual reality (VR) allows users to provide immersive experiences beyond the limits of the real world (Mostafa et al., 2014). These emerging virtuality-reality technologies have applications in different fields of life, i.e., healthcare, engineering, design, robotics, automotive, industrial, manufacturing and design, marketing and advertising, construction, education, agricultural training, military operation, entertainment, and tourism etc (Mirza et al. 2022). For González (2020), recent advances in VR technology have also made it possible to create, apply, evaluate, and deliver interactive applications at a lower cost.

The growing interest in the use of immersive technologies, driven by advances in high-quality hardware and software, has fostered the evolution of this field (Fonnet & Prié, 2021).

According to Xie (2021), immersion is a defining characteristic of VR, allowing the user to be transported to a totally virtual world, distancing themselves from physical reality, mainly through sight and hearing.

This project consists of a technical report of prototyping focusing on the developed hardware (Scalpel) and its integrations with the Meta Quest 2 glasses and 3D virtual environment developed in Unity. The XIAO SEEED nRF52840 SENSE board, which uses Nordic's nRF52840 controller, was studied in order to establish a systematic programming and implementation of communication via Bluetooth so that it can connect to the Meta Quest 2 glasses, transmitting the processed data from the accelerometer and gyroscope to the Meta Quest 2 glasses, the device will have 4 digital buttons and a trimpot to adjust the sensitivity.

This work describes the development of a scalpel with sensors and actuators, connected via BLE to the Meta Quest 2 glasses with an immersive virtual reality environment developed in Unity, allowing surgical practice with tactile feedback through different levels of scalpel vibration, depending on the type of tissue being manipulated in the virtual reality environment.

METHODOLOGY

This article presents a technical report on the development of a prototype haptic scalpel with Bluetooth Low Energy (BLE) communication, designed for integration with immersive virtual reality environments through the Meta Quest 2 glasses. The main objective of this work is to describe the creation of a prototype that enables physical and tactile interaction between the user and a simulated surgical training environment.

The methodological process was structured on three integrated development fronts:

i. Electronic hardware: The circuit was implemented using the Seeed XIAO BLE Sense module (nRF52840), which incorporates BLE connectivity and embedded computational resources. Inertial sensors were connected - 1 analog accelerometer (ADXL335) and 1 digital gyroscope (LSM6DS3) to collect movement and orientation data. 4 physical buttons have been included for digital input of commands. 2 vibration motors, controlled via transistors, were added to provide tactile feedback during the simulation. The system is powered by a 3.7 Volt Li-Po battery. The circuit layout was developed in electronic CAD software (KiCad) and later manufactured and assembled, including physical encapsulation through modeling and 3D printing of the scalpel housing.

ii. Embedded Firmware: The firmware was developed on the Arduino platform. The main logic comprises: reading the sensors (with the application of filters and bias compensation), detecting events in the buttons, encoding the sensory data in compact packages and transmission via BLE. The system also interprets commands received from the virtual environment, controlling the vibration motors selectively, according to the intensity and time defined in the control message.

iii. Interactive virtual environment: The application was developed in the Unity engine, using the asset "Bluetooth LE for iOS, tvOS, and Android" to communicate with the prototype via BLE. The virtual environment simulates an operating room, including a visual representation of a human body and interaction with the scalpel. Specific scripts pair with the physical device, process the received data, and update the position and rotation of the virtual scalpel. Haptic feedback is activated according to simulated cutting events in different layers (skin, muscle, bone), generating commands that are sent to the hardware.

This approach allowed the prototyping of a functional system with two-way communication between the hardware and the virtual environment.

MATERIALS

The prototype was assembled using the following main materials:

- Meta Quest 2: Virtual reality headset used to view the simulation
- Seeed XIAO BLE Sense nRF52840 module: microcontroller responsible for sensor data collection and BLE communication;
- Accelerometer ADXL335: three-dimensional analog acceleration sensor;
- 10kΩ trimpot: manual adjustment of the intensity of movement of the scalpel;

- Li-Po 3.7V 500mAh battery: system power supply;
- Vibration motors: actuators responsible for tactile feedback;
- Push buttons: used for manual user interaction with the VR environment;
- Auxiliary electronic components: resistors, transistors, diodes, and connection cables. Each component has been selected in order to optimize the relationship between performance, energy consumption and integrability with virtual reality systems.

PROTOTYPE DEVELOPMENT

Implementing the scalpel integrated with the virtual reality environment requires a structured approach that encompasses hardware, firmware, and software, ensuring synchronization between the physical device and the virtual environment. The development of the system was based on a set of electronic components, Bluetooth Low Energy (BLE) communication protocols and integration with the Unity environment for surgical simulation on the Meta Quest 2.

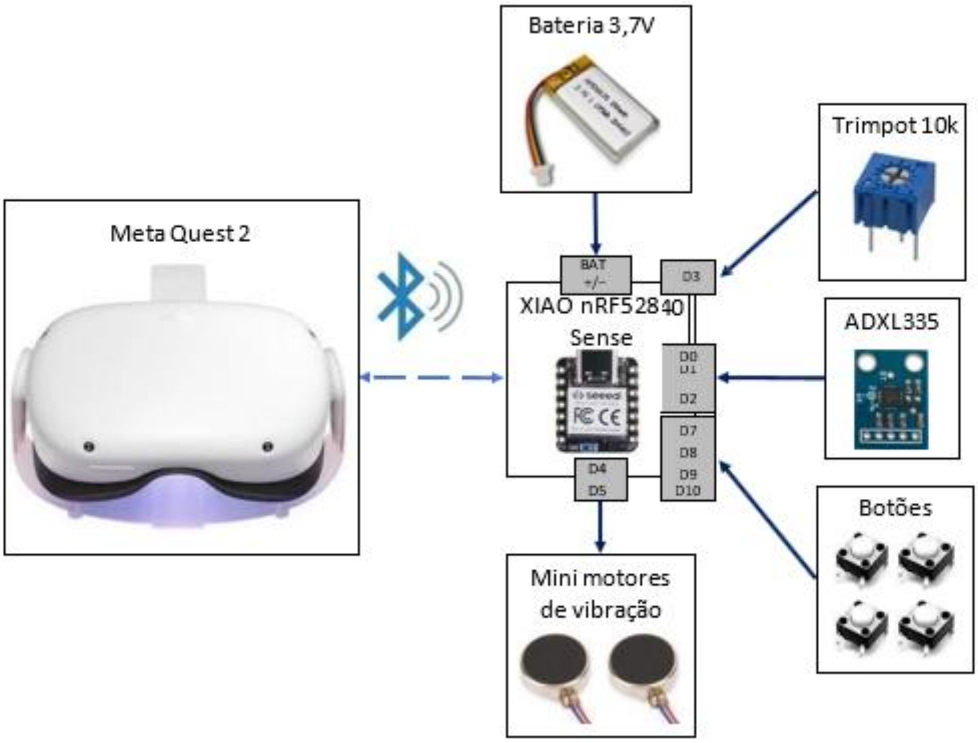
The development approach followed the following steps:

1. Design and assembly of the hardware – Definition of the components, elaboration of the electronic circuit and manufacture of the PCB.
2. Firmware development – Implementation of the embedded code for capturing data from the sensors, activation of vibration motors and BLE communication.
3. Virtual reality environment setup – Implementation of the operating room in Unity, modeling of the virtual scalpel, and integration with Meta Quest 2.
4. Implementation of BLE scripts in Unity – Development of code for communication between the scalpel and the simulation, ensuring that the movements of the physical scalpel are correctly reflected in the virtual environment.

In addition, to ensure low power consumption and efficient communication, the Bluetooth Low Energy (BLE) protocol was used for data transmission between the scalpel and the Meta Quest 2. This makes it possible for information such as scalpel movements, button presses, and haptic feedback via vibration motors to be sent in real-time, creating a more immersive and realistic surgical simulation experience.

Figure 1 presents the circuit diagram that illustrates the integration of the electronics with the Meta Quest 2 virtual reality device via Bluetooth Low Energy communication.

Figure 1 - Block diagram



Source: Author, 2025.

The diagram in Figure 1 illustrates the structure of the immersive virtual reality medical simulation system, with the Meta Quest 2 as the main interface. The Seeed XIAO BLE Sense nRF52840 microcontroller is responsible for managing communication via Bluetooth Low Energy (BLE), receiving and sending data from sensors and actuators to the virtual environment in real time.

The Seeed XIAO BLE Sense nRF52840, located in the center of the diagram, connects to the following key components:

- ADXL335 accelerometer (gates D0, D1 and D2): Captures acceleration in the X, Y and Z axes, allowing the monitoring of movements and inclinations, essential for interaction in the virtual environment.
- 10kΩ Trimpot (D3 port): Allows you to adjust the sensitivity of movements or the speed of system response, providing a personalized user experience.
- Vibration motors (D4 and D5 ports): Provide haptic feedback to the user, simulating physical sensations during interaction with virtual objects. This increases the immersion and realism of the simulation, especially in surgical scenarios.
- Push buttons (ports D7 to D10): These act as a manual control interface, allowing the user to execute specific commands, such as selections or adjustments in the virtual environment.

- The Li-Po battery provides power for the entire system, connecting to the microcontroller to ensure autonomous and continuous operation, with a charging circuit integrated into the Seeed XIAO BLE Sense module.

The system aims to provide an immersive and responsive experience by integrating motion and control data with the virtual reality environment through the Meta Quest 2. Communication via Bluetooth Low Energy ensures data transmission with low latency, essential for interactions in the virtual environment to be replicated accurately and in real time.

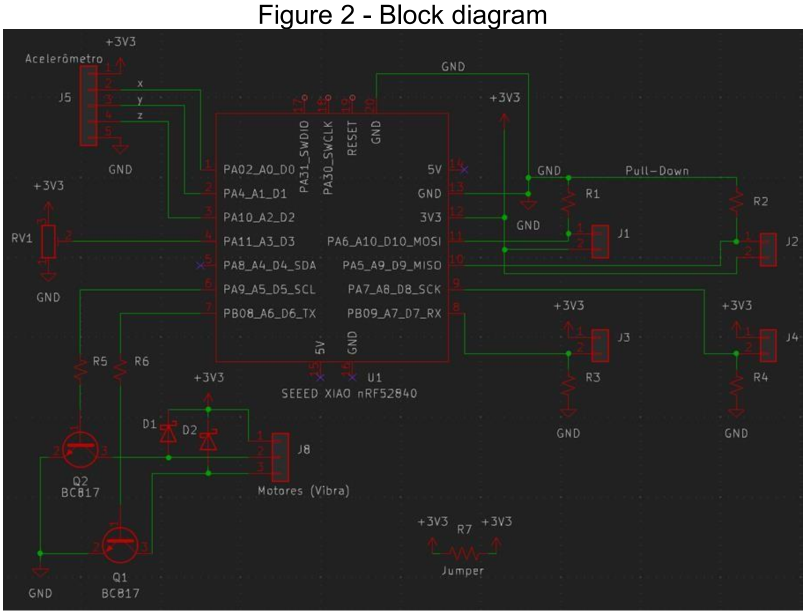
The haptic feedback, provided by the vibration motors, is synchronized with the actions performed in the virtual environment, simulating, for example, the touching of surgical instruments on fabrics, increasing the fidelity of the simulation.

Mounting the Hardware

Initially, the electronic circuit was designed on a protoboard, interconnecting the sensors, actuators and the microcontroller. The connections were validated to ensure the stability of the signals and the protection of the components, using pull-down resistors and protection diodes against reverse voltages generated by the motors.

The schematic diagram shown in Figure 2 illustrates the circuit responsible for communication between the Seeed XIAO BLE Sense nRF52840 module, sensors, actuators, and other components in the system.

Figure 2 - Block diagram



Source: Author, 2025.

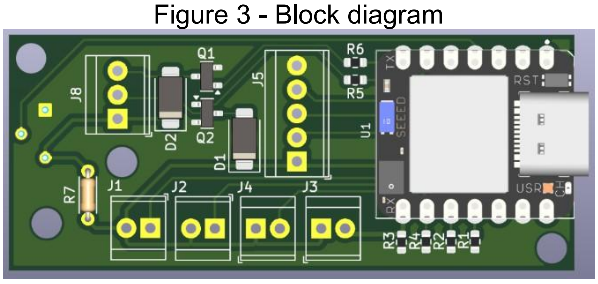
This circuit integrates the accelerometer, which detects movements in three axes, and the vibration motors, which provide haptic feedback. The knobs and trimpot provide manual control and sensitivity adjustments to the system. The Seeed XIAO BLE Sense nRF52840 module coordinates all these inputs and outputs and transmits data to the Meta Quest 2 via Bluetooth Low Energy (BLE), allowing user interaction with the virtual reality environment in real time.

Subsequently, a printed circuit board (PCB) of approximate dimensions of 60 mm x 25 mm was developed, designed to optimize the distribution of components and minimize electromagnetic interference.

Figure 3 shows the arrangement of the main components on the PCB.

- The J8 connector is allocated for the connection of the vibration motors, which provide tactile feedback to the user.
- Connectors J1 to J4 are used to connect control buttons, which allow the user to interact directly with the system.
- The accelerometer is plugged into the J5 connector, monitoring movements in the X, Y, and Z axes.
- Diodes D1 and D2 are used to protect the circuit against voltage spikes generated by vibration motors, while BC817 transistors (Q1 and Q2) control the activation of the motors.
- The Seeed XIAO BLE Sense nRF52840 (U1) module is the core component of the PCB, receiving the signals from the sensors and controlling the actuators.

Figure 3 - Block diagram



Source: Author, 2025.

Firmware Development

The embedded firmware was developed in the Arduino IDE, using specialized libraries such as "bluefruit.h" and "Adafruit_TinyUSB.h". The code has been structured to:

- Capture data from the accelerometer and gyroscope;
- Process button and trimpot commands;
- Drive the vibration motors via PWM;
- Transmit sensory data via BLE using the GATT protocol.

Digital filters were applied to reduce noise and improve the accuracy of the data sent to the virtual environment. Preliminary tests ensured the stability of BLE communication and the integrity of transmitted packets.

All the firmware was developed in order to integrate all the hardware components, the result can be seen in Figure 4 presents the main structure of the code.

Figure 4 - Main Code Structure

```
nRF52840_BLE_GATT_v2.ino    main.h

#include "main.h"

BLEDis bledis;
BLEService customService = BLEService(0x1234);  // UUID personalizado para seu serviço
BLECharacteristic allDataChar = BLECharacteristic(0xFFFF);
BLECharacteristic motorControlChar = BLECharacteristic(0x2C03);
LSM6DS3 internal_IMU(I2C_MODE, 0x6A);

void setup() {⋯
}

void loop() {⋯
}

void initPeriphels() {⋯
}

float updateAxisData(int axisPin, float bias) {⋯
}

uint8_t checkButtons() {⋯
}

void calibrateGyroscope() {⋯
}

void int1ISR() {⋯
}

void onMotorControlWrite(uint16_t conn_hdl, BLECharacteristic* chr, uint8_t* data, uint16_t len) {⋯
}
```

Source: Author, 2025.

The firmware efficiently integrates hardware control (accelerometers, gyroscopes, vibration motors, and buttons) with BLE communication, enabling the creation of a haptic interface for surgical simulations in virtual reality environments. The use of a low-pass filter to compensate for the impact of vibrations, along with sending real-time data via BLE, makes this firmware a viable solution for interactive and immersive simulations. The code's modularity and scalability allow it to expand to other devices and functions, making it suitable for future applications in human-machine interfaces in simulated medical environments.

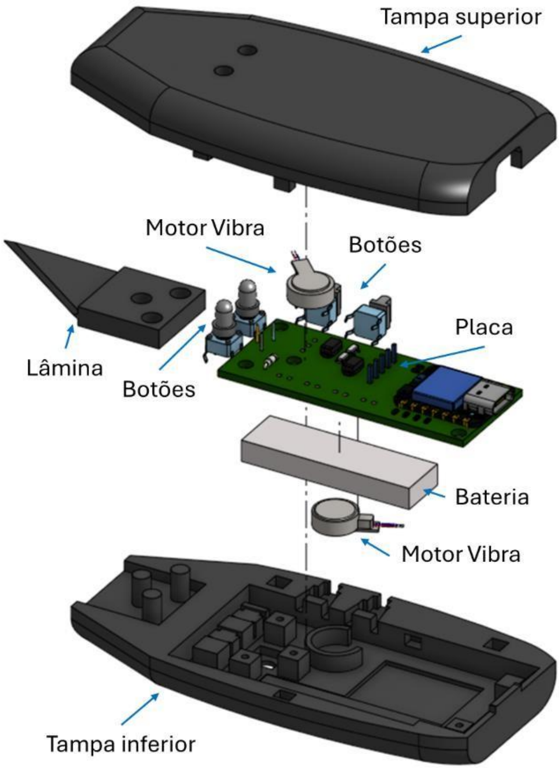
Mechanical Design

The scalpel shell was designed in 3D modeling software (OnShape) and produced via 3D printing using PLA (polylactic acid) material. The design prioritized ergonomics, lightness and the balanced distribution of internal components. The internal structure was planned to allow easy access to the battery and the electronic board, as well as to ensure correct heat dissipation.

After the design was completed, the scalpel was 3D printed and assembled with all the internal components, such as the plate with its components, vibration motors, and the buttons.

Figure 5 illustrates the final design of the scalpel, with an exploded view showing the distribution of the internal components and how they fit into the external structure.

Figure 5 - Exploded view of scalpel and components



Source: Author, 2025.

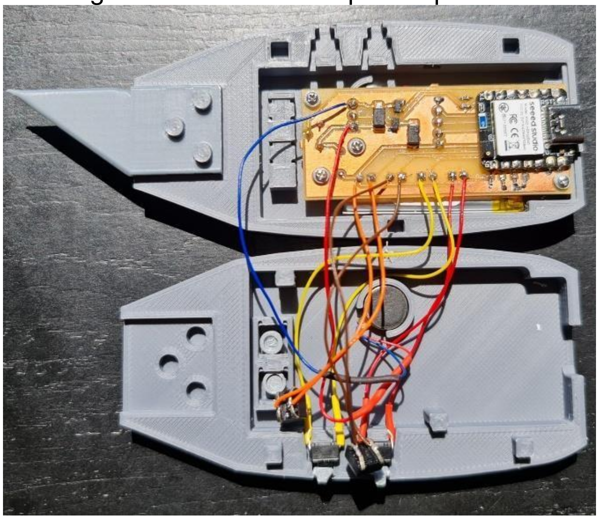
Implementation of the system

The printed circuit board was designed based on the previously validated circuit on the protoboard, using the SEEED XIAO BLE nRF52840 Sense as the main controller.

The manufacture of the printed circuit board was carried out on a CNC milling machine (board mill), using a simple phenolite board.

Figure 6 shows the plate fully assembled and connected to the scalpel case.

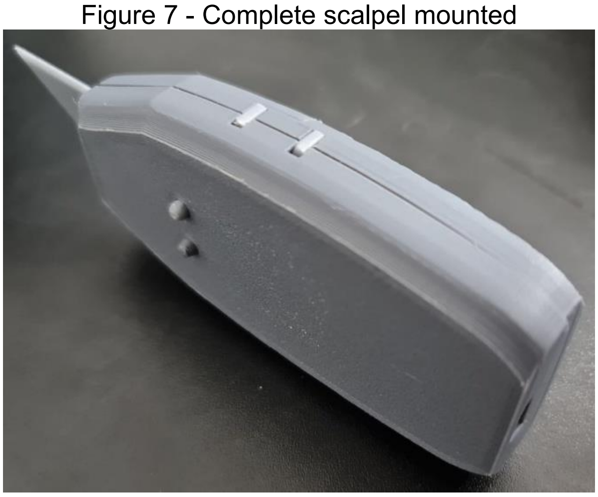
Figure 6 - Mounted scalpel in operation



Source: Author, 2025.

The scalpel case is designed to accommodate all electronic components. The result of the prototype, already assembled and functional, can be seen in Figure 7.

Figure 7 - Complete scalpel mounted



Source: Author, 2025.

With the hardware assembly and firmware development completed, integration with the virtual reality environment was carried out. The scalpel has been set to automatically connect to the Meta Quest 2 via BLE, continuously transmitting movement and button press data.

Scripts developed in C# in Unity allowed the reading of BLE characteristics, the interpretation of sensory data and the control of three-dimensional models in the virtual environment, synchronizing movements and haptic responses.

VIRTUAL ENVIRONMENT SETUP

The surgical simulation environment was developed on the Unity platform, using the XR Interaction Toolkit package for integration with Meta Quest 2. Custom scripts have been created for:

- Scan and pair BLE devices;
- Capture data from the sensors and translate it into virtual scalpel movements;
- Implement the logic of cutting three-dimensional meshes and generating haptic feedback.

The virtual environment is designed to be intuitive and provide a fluid immersive experience, with reduced latency and adequate sensory response. The virtual operating room allows direct interaction with objects such as tissues and surgical instruments, simulating realistic procedures.

The interface design prioritized usability, allowing the user to interact with the virtual scalpel and perform simulated operations in a natural manner. The use of tactile feedback associated with the virtual cut reinforces perceptual immersion and realism during activities.

Figure 8 presents a view of the developed environment, showing the three-dimensional meshes of the virtual human model used in the simulations.

Figure 8 - Virtual human model with its visible meshes in unity

Source: Author, 2025.

RESULTS

To evaluate the accuracy and sensitivity of the onboard sensors, controlled movement tests were performed using known angles of inclination and rotation. The objective was to verify how much the movement captured by the sensors (analog accelerometer ADXL335 and digital gyroscope integrated into the nRF52840) correspond to the real movement applied to the physical scalpel, later reflected in the virtual environment. During the tests, readings were recorded in three axes for acceleration and three for rotation, with continuous sampling via BLE. Table 1 presents the mean absolute errors (EMA) for each axis, comparing the expected motion with the motion reported in Unity:

Table 1 – Mean absolute errors of each axis

Axis	Mean Absolute Error (g or °)	Standard deviation	Observations
Accelerometer X	0.12g	0.04g	Slight noise at low amplitude
Y accelerometer	0.09g	0.03g	Stable after calibration
Z Accelerometer	0.15g	0.05g	Increased sensitivity to vibration
Gyro X	1,8°	0,9°	Responds well to fast revs
Gyro Y	2,1°	1,0°	Subject to uncorrected drift
Gyro Z	1,4°	0,8°	Good linearity at plane speeds

Source: Author, 2025.

For a BLE device with a battery, low power consumption is crucial, to measure this power consumption, the current measurement of the main components of the circuit was carried out.

The scalpel was connected via BLE to continuously transmit the movement data and the vibration motors were periodically activated, simulating a more intense use scenario. The device operated stably for 10 hours, sending this information uninterruptedly. Table 2 shows the current consumption of the components.

Table 2 – Current consumption of the components

Test performed for 10h (until battery depletion)			
Component	Maximum current	Ma	mAh consumption
Engine 1	90mA	90,0	193,50
Engine 2	90mA	90,0	193,50
XIAO Module	10mA	10,0	100,00
ADXL335	350uA	0,35	3,50
Button	330uA	0,33	0,66
			491,16

Source: Author, 2025.

Each simulated tissue type (skin, muscle, and bone) was mapped to a specific vibration pattern to provide the user with distinct sensations during the virtual cut. The intensity and duration of the vibration were determined based on the density and strength of the tissue, as shown in Table 3.

Table 3 – Comparison between the vibration system

Axis	Intensity (PWM)	Duration (ms)	Observations
Skin	50%	250	Lightweight, continuous vibration
Muscle	75%	500	Medium and continuous vibration
Bone	100%	1000	Intense and continuous vibration

Source: Author, 2025.

Tests were carried out with continuous sending of packages for about 10 minutes at different distances. No significant packet loss was observed in tests up to 2 meters away and without direct interference from other BLE devices. Data integrity was preserved in more than 99.8% of cases, which corroborates the reliability of the solution. Figure 9 presents the results obtained, the red dots on the graph represent the packets that were received, each packet has all the information (accelerometer (X, Y and Z), gyroscope (X, Y and Z), buttons pressed and module temperature), the values in dBm represent the strength of the received signal (it is related to the distance, the better the value, the greater the distance between the devices) and finally the values in milliseconds (ms), represent the latency (time difference between sending and receiving the packet). The tests performed indicated an average latency of 22 milliseconds for BLE communication.

Figure 9 - Data received from the scalpel

Source: Author, 2025.

Table 4 presents a comparison between the system developed in this study and other similar devices found in the literature, with emphasis on parameters such as type of connection, sensors used, presence of tactile feedback and integration with interactive 3D platforms.

Table 4 – Comparison between developed systems

Project / Reference	Connection	Haptic Feedback	VR Integration	Sensors used	Observations
Surgical simulation system (Li et al., 2022)	USB	Yes	Yes	Strength, movement, haptic feedback	Uses device with resistance simulated for cuts
Laparoscopy Simulator (Abinaya, 2023)	Serial cable	Yes	Yes	Strength accelerometer	Large physical structure, without portability
Haptic Glove Device (Sense Gloove, 2023)	BLE	Yes	Yes	Flex, Vibration, IMU	Used as a glove; does not simulate scalpel
VR Scalpel (This work)	BLE	Yes	Yes	Analog accelerometer, gyroscope digital, vibration	Portable, customizable, use with Meta Quest 2

Source: Author, 2025.

These results demonstrate that the system can be fast enough and robust enough for surgical training applications with real-time sensory feedback.

DISCUSSION

The performance evaluation of the sensors showed that the analog accelerometer (ADXL335) showed greater sensitivity to vibration in the Z axis, while the gyroscope integrated into the nRF52840 module showed greater susceptibility to accumulated deviations (drift) in the Y axis, particularly in prolonged movements. These deviations can be minimized with the application of complementary filters or sensory fusion, which represents a possibility for future improvement.

The autonomy of 10 hours of continuous operation was obtained even with periodic activation of the vibration motors and continuous data transmission via BLE, which highlights the balance between energy consumption and system performance. The analysis of current consumption by component showed that vibration motors represent the largest portion of energy consumption.

The architecture based on the GATT protocol made it possible to define customized BLE services and characteristics that allowed the segmentation of data into different channels, optimizing the sending of sensory information (acceleration, rotation, buttons) and the receipt of haptic commands (intensity and duration of the PWM of the motors). This modular structure favored the scalability of the system, and could be expanded to include new features or additional commands without compromising the stability of communication.

The literature review allowed us to identify that, although there is ample literature on haptic devices and medical simulators based on virtual reality, no study reports the construction and validation of physical scalpels with wireless communication and integrated tactile feedback to immersive environments in real time. Most of the devices described in the literature, such as laparoscopic simulators or haptic gloves, use larger physical structures or systems with less portability, and with limited integration to mobile platforms such as the Meta Quest 2.

The haptic feedback system designed in this work mapped different layers of tissue (skin, muscle, bone) to distinct vibration patterns, using pulse width modulation (PWM) and duration control. This approach made it possible to tactile differentiation between the types of fabric represented in the virtual simulation. The practical implementation showed consistency in the activation of the actuators according to the cut-off events recorded in Unity, with adequate synchronization to the visual and tactile response.

The integrity of the received data packets was greater than 99.8% during continuous test sessions lasting up to 10 minutes and distance of up to 2 meters. The average latency observed was 22 ms, which is compatible with the minimum requirements for interactive simulation applications in virtual reality. The comparison with similar systems indicated that the present project has complementary characteristics, such as the use of mixed sensors (analog and digital), tactile feedback by vibration and complete integration with the Meta Quest 2 via BLE, not requiring a computer connection by USB cable.

In summary, the results obtained demonstrate possibilities for improvement in terms of signal filtering and adaptation of the virtual environment to different simulated surgical contexts.

CONCLUSION

This work presented the development of a haptic surgical scalpel with Bluetooth Low Energy communication, integrated into an immersive virtual reality environment based on the Meta Quest 2. The results obtained demonstrated the efficiency of the system in terms of latency, sensory accuracy, communication robustness and energy autonomy.

One of the main innovations of this work is the implementation of a real-time tactile feedback system, associated with the simulation of cuts in different anatomical layers in the virtual environment, using Unity deformations. The haptic response was performed by two PWM-controlled vibration motors, activated via BLE commands received by the physical scalpel. The observed low latency allowed for real-time interaction between the user and the virtual environment, making it suitable for surgical training applications.

The modularity of the device and the adopted architecture allow future expansion to additional functionalities, such as the automatic adaptation of haptic feedback via machine learning algorithms, or the extension of the application to other areas of health and technical training.

In conclusion, the developed prototype represents a potential breakthrough for immersive simulation-based teaching technologies, offering an effective, affordable, and adaptable solution for medical training and related applications.

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