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Development of an Intuitive Glove-Based Human Interface for Robotic Applications

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Abstract: This paper focuses on developing an innovative glove that enables users to control robots through natural hand gestures. The primary goal is to simplify human-robot interaction, allowing individuals to communicate with robots without extensive training or technical knowledge. The glove has three types of sensors: an ultrasonic sensor for measuring distances, flex sensors for tracking finger movements, and a GY-521 accelerometer for monitoring the hand's position and motion. By integrating these technologies, the glove translates simple hand gestures into precise commands for robotic systems, making it a powerful tool for various applications. This project attempts to bridge the gap between human actions and robotic responses, making technology more accessible and user-friendly. In summary, the glove-based control system has the potential to transform how individuals interact with robots. By utilizing simple hand gestures, users can perform complex tasks more effortlessly, which could be particularly beneficial in fields such as healthcare, manufacturing, and assistive technology. The research aims to pave the way for more effective and engaging robotic systems that cater to a wide range of needs, enhancing how people live and work alongside technology.

Keywords: Wearable Technology; Human-Robot Interaction; Biologically-Inspired Design; Bio Mimetics

1. Introduction

Wearable technology is becoming increasingly important in robotics, changing the way people interact with machines. As robots advance, there is a growing demand for easy-to-use control systems that allow users to operate robots smoothly and intuitively. This project focuses on developing a glove-based control system that enables users to manipulate robots through a set of built-in sensors. The glove features an ultrasonic sensor to measure distance, flex sensors to track finger movements, and a GY-521 accelerometer to monitor the position and motion of the hand. Together, these components aim to mimic human gestures, making it simpler for users to control robotic devices.

The inspiration for the development of this device comes from the purpose of developing robotic systems that are accessible and practical for various uses, such as in factories, healthcare settings, or assistive devices. Conventional robotic control methods often rely on complicated interfaces that can be difficult for everyday users to understand. By using a glove that translates natural hand movements into robot commands, this project aims to make it easier for people to control robots without needing extensive training or technical skills.

To build a solid foundation for the glove's design, a thorough literature review was conducted. This review looked at different methods and technologies previously used in human-robot interaction, highlighting what worked well and what did not. By studying past research, key features were identified that would make the glove effective. This approach not only helped shape the glove's initial design but also highlighted areas for potential improvement.

The proposed design follows a clear methodology that includes several stages: design, prototyping, and testing. In the design phase, suitable sensors and materials are chosen to ensure the glove is both functional and comfortable to wear. During prototyping, an initial version of the glove is built, which is crucial for testing how well the sensors work together in real-life situations. This hands-on approach allows for adjustments based on how the glove performs in practice. Testing is a vital part of the project as it validates the glove's capabilities. Each sensor will be tested both individually and together to see how well they function. The ultrasonic sensor is expected to detect distances accurately, confirming its usefulness in avoiding obstacles. The flex sensors should accurately measure finger movements, showing that they can effectively control robotic grippers and perform tasks that require precise manipulation. The GY-521 accelerometer will capture hand movements across three dimensions, demonstrating the glove's ability to replicate complex hand gestures for robotic use.

Through this project, the goal is to create a glove-based control system that enables real-time motion capture, detects objects, and provides interactive control for robotic devices. The project aims to bridge the gap between human intention and robotic action, creating a more intuitive interface that enhances user experience. The insights gained from this research will contribute to existing knowledge and set the stage for future developments in wearable technology and robotics. Ultimately, this project aspires to lead to more effective and user-friendly robotic systems that can be used in various industries, benefiting both users and society.

In "Comparison of Hand Gesture Inputs Using Leap Motion Controller & Data Glove in a Soft Finger", Medagedara compares the performance of a Leap Motion Controller and a data glove for controlling a soft robotic finger [1]. This comparison is relevant for this project as one of the three sensors utilised in this project, alongside the GY-521 accelerometer and ultrasonic sensors for robotic control, is flex sensors. Medagedara's findings indicate that the data glove provided better real-time feedback and precision than the Leap Motion Controller, making it more suitable for robotic control applications. The challenges talked about in this study in translating human gestures into robotic movements help provide more information on the fine-tuning of the flex sensors, which would help in this project, thereby improving accuracy in controlling robotic systems [1]. In a second piece of research titled "Design of Underwater Humanoid Flexible Manipulator Motion Control System Based on Data Glove", Xu explores how a data glove can be used to control underwater robotic manipulators [2]. This system, which incorporates multiple sensors, closely relates to this project, where the integration of the GY-521 and ultrasonic sensors will be utilised. Xu highlights the significance of sensor fusion, demonstrating that the combination of sensor data can enhance the accuracy and control of robotic systems. This study helps this project, as the integration between the GY-521 accelerometer, gyroscope, and flex sensors will be critical for achieving smooth and precise control in robotic applications [2]. Another study by Boka focuses on a pneumatic robotic glove used for rehabilitation, emphasising the adaptability and flexibility of soft robotics [3]. Although this project does not use pneumatic systems, the utilisation of flexible materials and sensors for human-robot interaction is the aim that will be taken in this project. Boka's design prioritises user comfort and accurate sensor placement, both of which are essential in the design of the glove for this project. The flex sensors will similarly translate hand gestures into precise robotic control while ensuring that the glove remains comfortable for extended use and ergonomically suitable for users, which is an aspect that Boka's design emphasizes [3].

In the study "Design, Control and Testing of Soft Pneumatic Rehabilitation Glove", Du details the integration of flex sensors in a soft rehabilitation glove designed for hand movement detection and robotic control [4]. Du's methodology in designing, testing, and calibrating the glove's sensors is related to the methodology that will be followed in this project. His emphasis on sensor calibration to enhance the responsiveness of the glove's movements provides valuable insights for the implementation of the flex sensors and GY-521 accelerometer in this project. Furthermore, Du's testing of the glove in various conditions serves as a model for how the project can validate the effectiveness of the glove controller in robotic control environments [4]. Tran et al. [5] discuss the design of a soft robotic exoskeleton glove for spinal cord injury rehabilitation, offering important insights into sensor integration for glove systems. While the focus here is more on rehabilitation, the talk of translating hand movements into robotic actions aligns closely with the objectives of this project. The flex sensors in Tran's glove capture hand gestures to control robotic systems, which are similar to the functions of the flex sensors in the glove being developed in this project. Tran's focus on ergonomics and ensuring that the glove is lightweight and functional further highlights the importance of comfort and practicality, which are critical aspects in the design of a glove for robotic applications [5]. Moreover, Lee's study investigates the effectiveness of various hand gesture input methods for *Virtual Reality*

(VR) gaming [6]. This research compares traditional VR controllers with data gloves to assess user experience and control accuracy. Lee's findings highlight that data gloves offer enhanced immersion and more natural interaction, allowing users to perform complex gestures more naturally than with standard controllers. This research is mostly relevant to the current project, as it highlights the importance of user experience in controller design. By incorporating flex sensors and gyroscopic sensors, such as the GY-521, the glove controller can influence insights from Lee's study to optimise gesture recognition and user comfort in robotic applications, ensuring it addresses the challenges of precision and intuitive control akin to VR environments [6]. Finally, the paper "Sensorized Fabric Glove as Game Controller for Rehabilitation" by Ghate explores the potential of a fabric glove embedded with sensors as a rehabilitation tool [7]. The study introduces a new approach to physical therapy by incorporating gamification into rehabilitation exercises, therefore enhancing patient engagement and motivation. The sensorized glove tracks hand movements and translates them into game controls, allowing users to interact with virtual environments while performing therapeutic exercises. Ghate highlights the importance of real-time feedback in rehabilitation, noting that immediate responses to movements can significantly enhance the effectiveness of therapy. This research closely aligns with this project of developing a glove controller that integrates flex sensors and gyroscopic sensors like the GY-521. From Ghate's work, the glove controller can be designed not only to control robotic applications but also to facilitate rehabilitation by providing engaging and interactive exercises. The focus on user experience and the potential for improving rehabilitation outcomes through gamification are some important considerations for the project, ensuring that the final product is both functional and user-friendly [7].

In conclusion, all the reviewed literature highlights the potential of glove-based controllers in enhancing user interaction and control within both rehabilitation and robotic applications. Medagedara's comparison of gesture inputs emphasises the advantages of integrating multiple sensor types for improved user experience [1]. Xu's design of an underwater manipulator showcases how data gloves can translate hand movements into precise controls [2]. Boka's KNTU-RoboGlove and Du's soft pneumatic rehabilitation glove underscore the importance of responsive designs in therapeutic contexts [3]. Tran's FLEXotendon Glove-III and Lee's user study on VR controllers reinforce the effectiveness of gesture-based controls [4–6]. Finally, Ghate's work on sensorized fabric gloves illustrates the benefits of gamification in rehabilitation [7]. Together, these insights will help guide the development of a glove controller utilising the GY-521, flex sensors, and ultrasonic sensors for enhanced robotic applications.

2. Materials and Methods

The experimental research method has been selected for this project because it helps with thorough testing and comparison of various components, such as flex sensors, the GY-521 accelerometer, and ultrasonic sensors, to evaluate their effect on the performance of the glove-based control system. By implementing controlled experiments, the project can generate precise, quantitative data on the effectiveness of each sensor configuration in translating hand movements into robotic actions. This systematic approach not only enables researchers to identify the strengths and weaknesses of different setups but also supports the iterative refinement of the glove's design and functionality. Furthermore, the insights gained from these experiments will guide the optimisation of sensor combinations, ensuring that the final system is both effective and reliable for a wide range of robotic applications. The importance of experimental data collection and analysis will finally contribute to the development of a glove controller that meets the demands of precision and responsiveness in real-world scenarios.

The main aim of this study is to develop a glove-based control system specifically designed for various robotic applications. This system will combine the use of flex sensors and accelerometers, all powered by an Arduino platform. The robotic applications targeted in this project will encompass robotic arms, rehabilitation devices, and manufacturing tools, demonstrating the flexibility of the glove-based controller. To achieve this aim, the objectives of the research are defined as follows:

- **Requirements and Specifications:** This initial phase will involve a comprehensive review of existing glove-based control technologies, focusing on their functionality and effectiveness in robotic applications.
- **Prototype Manufacturing:** The next objective is to design and construct the glove, ensuring that the placement of flex sensors and accelerometers is optimised for accurate movement detection and comfort.
- **Software Development:** Following the construction, the programming phase will include developing the necessary code to process sensor data and translate hand gestures into commands for the robotic systems.

- **Testing:** Multiple tests will be done to evaluate the performance and reliability of the glove in real-world applications, focusing on aspects such as responsiveness and precision.
- **Review:** Finally, the project will conclude with a detailed report that documents the methodology, findings, and implications of the glove-based control system, offering valuable insights for future research and development in this area.

This approach ensures that each phase of the project builds on the previous one, enabling the successful development of a functional and effective glove-based control system for robotic applications. Therefore, completing the main aim stated above.

2.1. Hardware

The Hardware architecture of the system is made of 3 elements, namely (1) a sensor network, (2) a processing unit, and (3) a human interface. The overall setup of the system is shown in **Figure 1**.

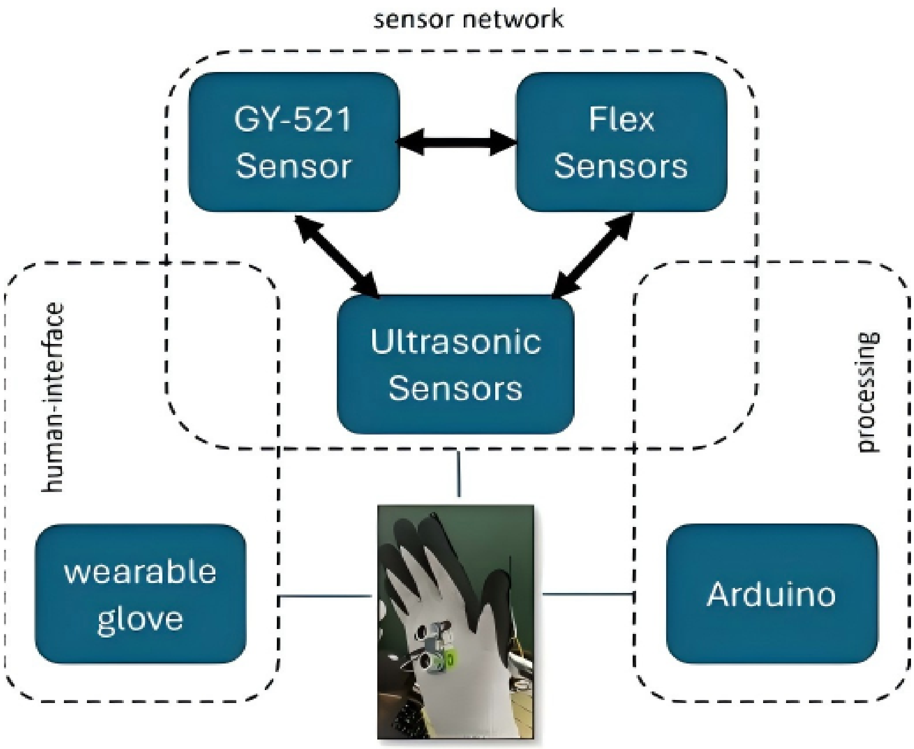

Figure 1. The architecture of the proposed system: A wearable glove embedding a sensor network is connected to a low-cost Arduino board in order to real-time monitor the flexions of fingers' phalanges and inertial movements of the palms, combined with object detection capability.

The following components were then adopted to develop the 3 units.

- **GY-521 Sensor:** This sensor is a compact module *Inertial Measurement Unit* (IMU) that incorporates a 3-axis gyroscope and a 3-axis accelerometer (*MPU-6050*). It is used to measure *angular velocity* and *acceleration*, providing crucial data for detecting hand orientation and movement in robotic control applications [8].
- **Ultrasonic Sensors:** Devices such as the HC-SR04 use sound waves to measure distance. They emit an ultrasonic pulse and listen for the echo, which can provide real-time feedback on the proximity of objects. This feature is beneficial for applications in robotic arms, allowing for collision detection and spatial awareness [9].
- **Flex Sensors:** These transducers are thin, bendable, resistive sensors that change their resistance based on the amount of bend or flexing they undergo. In this project, they will be used to detect finger movements by

placing them along the glove's fingers and translating these movements into corresponding commands for robotic applications [10].

The selection of flexible sensors combined with a glove made of fabric reflect the inherently properties of the system to adapt to the human hand: in the experience of the author vs wearable technologies it is important to design the system such as 'comfort' and 'adherence' reach a proper compromise vs the anthropomorphic parameter of the end-user without affecting the quality of the sensor data and the experience of the human subject.

An overview of these elements is shown in **Figure 2**.

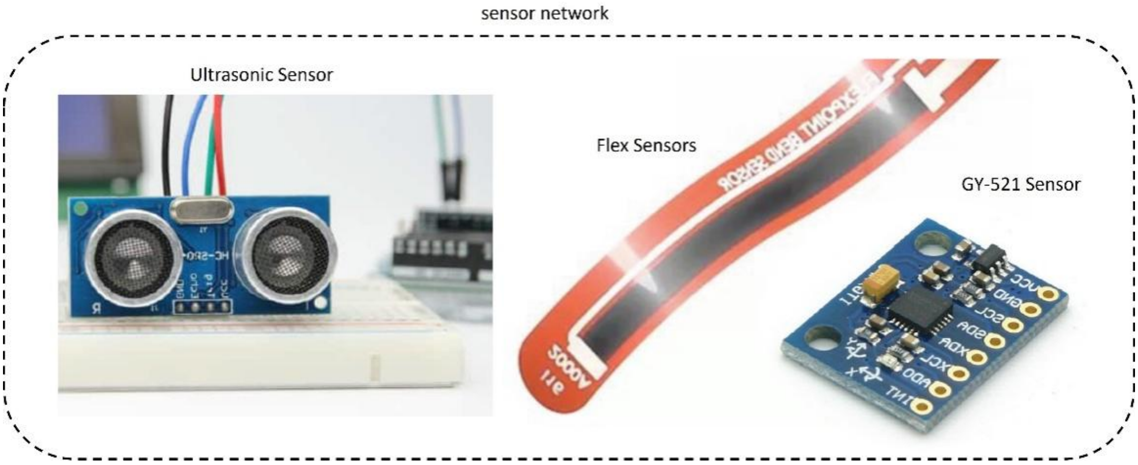

Figure 2. The sensor network is made of an ultrasonic sensor [9], a set of flex sensors [10], and a GY-521 sensor [11].

- **Arduino Uno R3:** This open-source system is a popular microcontroller board based on the *ATmega328P*. It serves as the central processing unit for the glove-based control system, handling input from the sensors and output to the robotic devices [12].
- **Arduino Software (IDE):** The Arduino *Integrated Development Environment* (IDE) is a cross-platform application that enables users to write, compile, and upload code to the Arduino board. It provides a user-friendly interface for programming the glove controller, allowing for the customisation of sensor data processing and robotic command execution [12].

A set of *cables* and *resistors* combined with a *breadboard* and a *9 V battery* was also adopted. Arduino cabling includes jumper wires and connectors used to establish connections between the sensors, the Arduino board, and other components. Proper cabling is essential for reliable data transfer and ensuring that the entire system functions correctly [13]. Resistors are passive electronic components used to limit current flow in circuits. Different resistors may be required for each sensor, depending on their specifications. For flex sensors, typically, a resistor in the range of 10k to 100k ohms is used to create a voltage divider, which helps convert the flex sensor's resistance change into a measurable voltage change [10]. A breadboard is a reusable platform for building electronic circuits without soldering. It allows for easy insertion and removal of components and wiring, making it ideal for prototyping and testing the glove-based control system before finalising the design [14]. A 9-volt battery connector provides a portable power source for the Arduino board, allowing the glove controller to operate independently of a computer. Alternatively, a USB wire can be used to power the Arduino while connecting it to a computer for programming and debugging purposes (Arduino, 2023).

2.2. Design and Integration

2.2.1. Wiring

A proper wiring was designed in order to implement the sensor network, as shown in **Figures 3** and **4**.

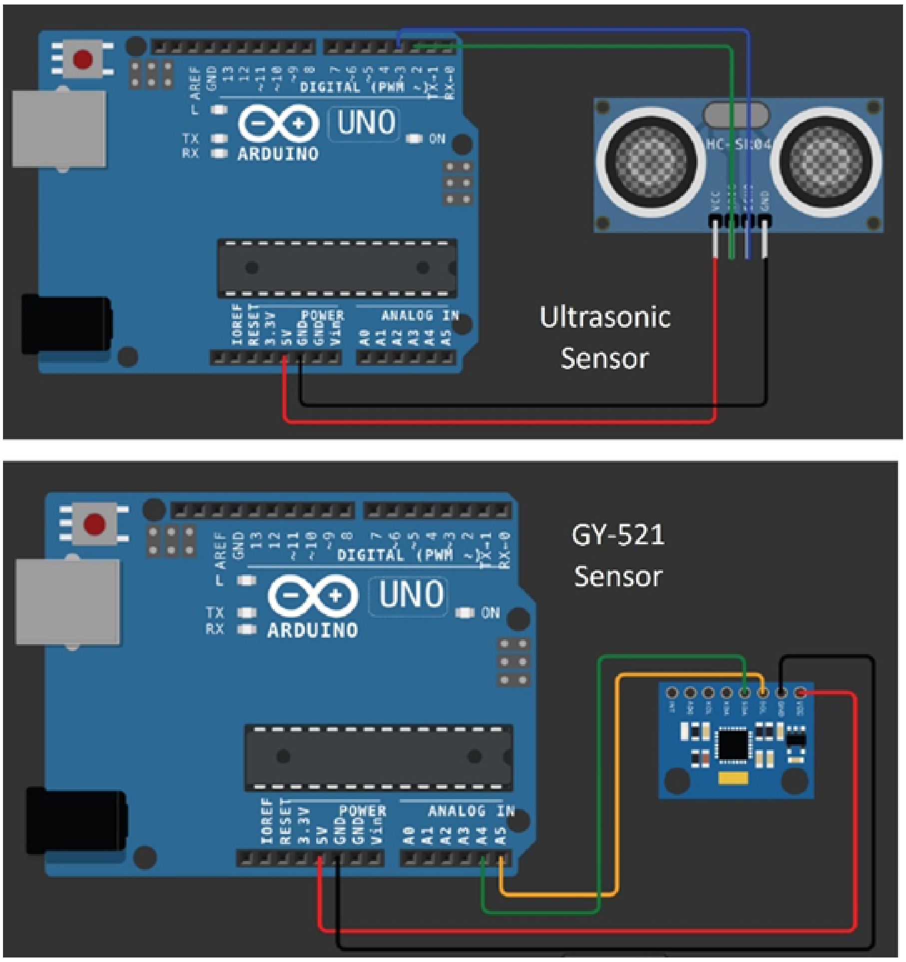

Figure 3. Wiring of the ultrasound sensor and of the GY-521 sensor on the top and bottom panels, respectively.

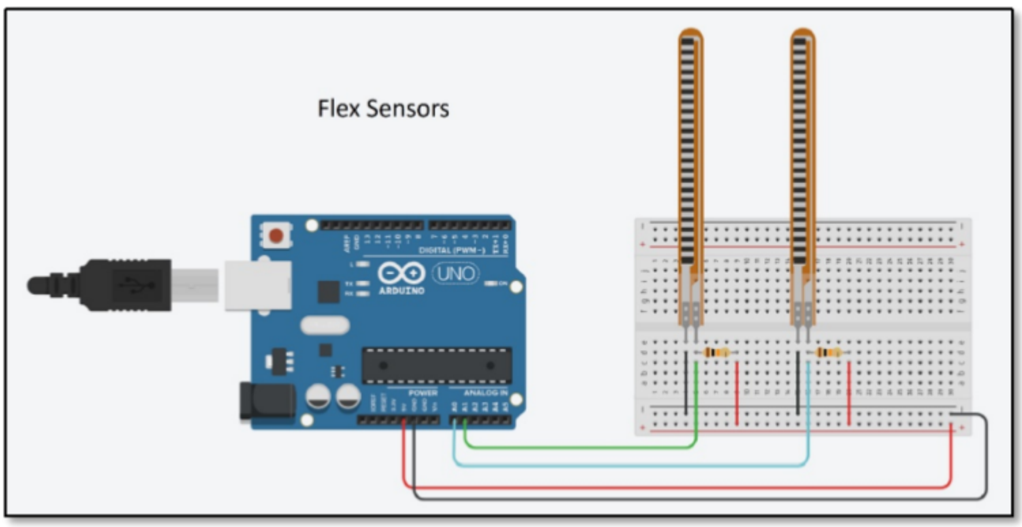

Figure 4. Wiring of the flex sensors.

GY-521 Wiring (Figure 3, Bottom Panel): The diagram shows how the GY-521 sensor is connected to an Arduino Uno using the I2C protocol, with the SCL and SDA pins connected to analogue pins A5 and A4 on the Arduino, and power provided through the 5V and GND pins. The GY-521 detects motion and orientation, and in combination with the additional sensors, ultrasonic and flex sensors, it allows the glove to interpret hand movements and control robotic actions effectively.

Ultrasonic Sensor Wiring (Figure 3, Top Panel): This figure illustrates the connection of the HC-SR04 ultrasonic sensor to an Arduino Uno. The sensor's VCC pin is connected to the Arduino's 5V pin, and the GND pin is connected to the Arduino's GND for power. The Trig pin is connected to digital pin 9, and the Echo pin is connected to digital pin 8 on the Arduino. This ultrasonic sensor works by measuring the distance of objects, and when combined with the other sensors, the GY-521 and flex sensors, it helps the glove accurately control robotic movements based on hand positioning and proximity detection.

Flex Sensor Wiring (Figure 4): This wiring chart shows the connection of flex sensors to an Arduino Uno. The flex sensor's end is connected to the 5V pin on the Arduino, while the other end is connected to the analogue pins A0 and A1 through resistors. The ground connections of the resistors are linked back to the GND pin on the Arduino. These flex sensors detect finger bending, and when used in conjunction with the GY-521 and ultrasonic sensor, they enable the glove to precisely interpret hand gestures and control robotic actions.

2.2.2. Glove Manufacturing and Sensors' Integration

To start with, following the wiring chart developed for the ultrasonic sensor, the sensor was installed on the Arduino uno board, ready to be programmed and tested. Then, following the wiring chart developed for the flex sensor, these sensors were installed on the Arduino uno board, ready to be programmed and tested. Finally, following the wiring chart developed for the GY-521 sensor, this was then installed on the Arduino uno board, ready to be programmed and tested. After wiring all the components and sensors to the Arduino uno board and the breadboard, all the components were first tested, which are shown in the testing section, and then from the realisation of the successful outcome of the tests, all the sensors were installed onto the glove for some final testing of the glove controller. Finally, for full testing, a 9 V battery pack was added to the glove to show that the glove does not always need to be plugged in, making it more efficient to fit the aims and objectives of this project and more successful towards robotic applications. **Figure 5** shows the results of this prototyping activity.

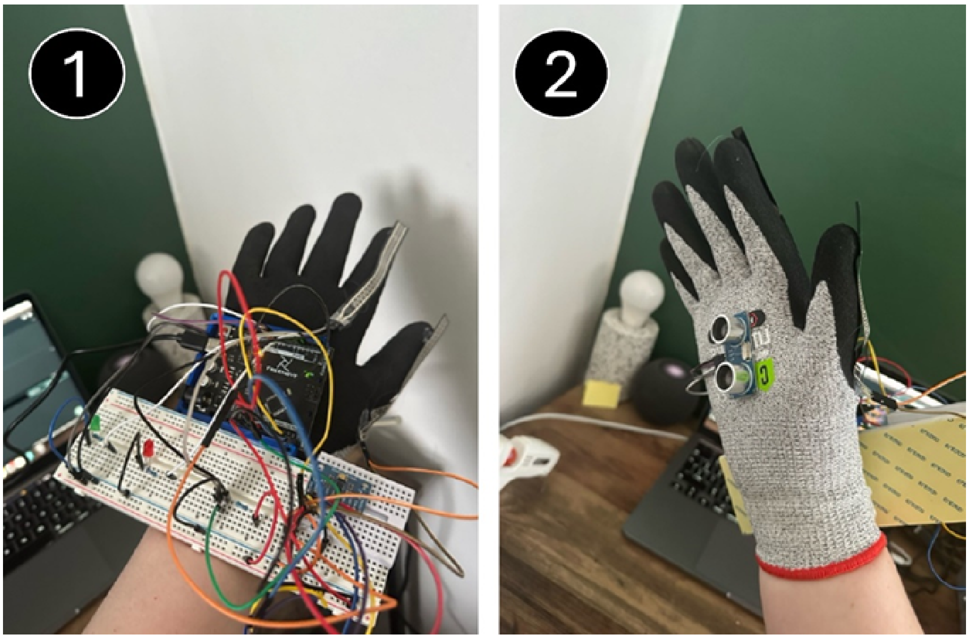

Figure 5. The (1) dorsal and (2) palm view of the glove prototype.

2.3. Software

To acquire and collect sensor data, proper coding must be implemented, which involves developing a set of functions leveraging the available SDK and libraries. The necessary libraries for *I2C communication* and the *MPU6050* *sensor* are included. An instance of the MPU6050 class is created to interact with the sensor. Several variables are declared to hold raw accelerometer readings for the *X*, *Y*, and *Z* axes, along with calibration offsets to correct these readings. Dynamic mapping limits are also initialised for each axis, setting initial maximum and minimum values.

The *setup function* initialises the serial communication for debugging at a baud rate of 9600. It begins I2C communication, initialises the *MPU6050 sensor*, and calibrates it to ensure accurate readings. Additionally, the pins for the two LEDs and the ultrasonic sensor are configured as output and input to prepare for sensor interactions and LED signalling. The *loop function* is executed continuously, reading data from the MPU6050 sensor using the *readSensorData* function. The raw accelerometer readings are adjusted by subtracting the calibration offsets. The adjusted values are then converted from raw units to 'g' units. Mapping limits are updated dynamically based on current sensor values. The accelerometer data is normalised to a range of −5 to 5 V using the *mapValue* function, and the mapped values for the *X*, *Y*, and *Z* axes are printed to the serial monitor for debugging.

The *readSensorData* function retrieves raw accelerometer data from the MPU6050 sensor (**Figure 6**). It uses the *getMotion6* method to read the values of the accelerations into temporary variables (namely, $a_x Raw$, $a_y Raw$, and $a_z Raw$). These raw readings are then stored in the global variables a_x, a_y, and a_z for further processing in the main loop. In the *calibrateSensor* function, the program averages multiple readings from the accelerometer to compute calibration offsets for each axis. It informs the user to keep the sensor still while taking 5000 readings, accumulating the *X*, *Y*, and *Z* values. After completing the readings, the average values are calculated and stored as offsets, which are printed to the serial monitor for verification (**Figure 7**). The *mapValue* function maps an input value from one range to another. It checks for a division by zero scenario to ensure the input range is valid. The function then performs the mapping calculation to convert the input value from the original range defined by *fromLow* and *fromHigh* to a new range defined by *toLow* and *toHigh*. This normalisation allows for consistent output across different ranges of input values. Finally, the *updateMappingLimits* function dynamically adjusts the minimum and maximum values for each axis based on the latest accelerometer readings. This ensures that the system can adapt to different conditions and maintains accurate mapping limits for the normalised output values, allowing for greater responsiveness to changes in the sensor's position or orientation.

```
void loop() {
    // Reading MPU6050 sensor data -----
    readSensorData(); // Getting accelerometer data
    ax -= axOffset; // Applying X-axis calibration offset
    ay -= ayOffset; // Applying Y-axis calibration offset
    az -= azOffset; // Applying Z-axis calibration offset

    // Converting raw accelerometer data to 'g' units -----
    float ax_g = ax / 16384.0;
    float ay_g = ay / 16384.0;
    float az_g = az / 16384.0;

    // Updating mapping limits based on current readings -----
    updateMappingLimits(ax_g, ay_g, az_g);

    // Mapping accelerometer data to a range of -5 to 5 -----
    float mappedX = mapValue(ax_g, xMin, xMax, -5, 5);
    float mappedY = mapValue(ay_g, yMin, yMax, -5, 5);
    float mappedZ = mapValue(az_g, zMin, zMax, -5, 5);

    // Outputting mapped MPU6050 data to serial monitor -----
    Serial.print("X:");
    Serial.print(mappedX);
    Serial.print(", Y:");
    Serial.print(mappedY);
    Serial.print(", Z:");
    Serial.println(mappedZ);
```

Figure 6. Program code snippet with the details of the IMU sensor readings.

```
void calibrateSensor() {
    float axSum = 0, aySum = 0, azSum = 0; // Initializing sums for calibration
    const int numReadings = 5000; // Number of readings to average for calibration
                                  // (The Higher the digit will make help smooth out any noise or fluctuations in the sensor readings.)

    Serial.println("Calibrating... Please keep the sensor still.");
    for (int i = 0; i < numReadings; i++) {
        readSensorData(); // Reading sensor data for calibration
        axSum += ax; // Accumulating X-axis readings
        aySum += ay; // Accumulating Y-axis readings
        azSum += az; // Accumulating Z-axis readings
        delay(2);    // Short delay between readings
    }
    // Calculating the average offsets for each axis -----
    axOffset = axSum / numReadings;
    ayOffset = aySum / numReadings;
    azOffset = azSum / numReadings;

    // Outputting calibration results  -----
    Serial.print("Calibration complete! Offsets - X: ");
    Serial.print(axOffset); Serial.print(" | Y: ");
    Serial.print(ayOffset); Serial.print(" | Z: ");
    Serial.println(azOffset);
}
```

Figure 7. Program code snippet with details of the MPU6050 accelerometer calibrations.

3. Results

This section presents a set of preliminary trials that were performed with the system, and then the results of these trials

3.1. Laboratory Tests

A set of 10 different tests was designed and prepared in order to preliminarily validate the different components of the system and the overall integrated system, namely *distance-tests*, *flex-tests*, and *XYZ-movements' tests*, as well as *output tests*, *glove tests*, and *live plotting tests*. All tests were performed in laboratory conditions. A description of these tests' set-up is reported within **Table 1**. Live demonstrations of some of these tests have also been reported within the **Supplementary Materials**' Section.

Table 1. Testing set-up with a description of the main outcomes (see also **Supplementary Materials**).

Test Type	Outcomes
Distance Test	This test shows the Ultrasonic sensors fully wired to the *Arduino* and programmed to measure the distance between themselves and an object. From the code as well, it outputs data onto a plot that shows the sensor working. In this case, the code has made it so that the distance sensor goes from 0–5 V depending on how close the object is to the sensor (this works alongside all the other sensor data that work in a margin of −5 V to +5 V).
Flext Test	This test shows the first flex sensor is fully wired up to the Arduino and programmed to see how strongly the sensor is being flexed. In this case, it is set from 0–2 V, 0 V being no flex and 2 V being fully flex. This allows robotic applications to open and close a gripper with ease when working together. This data is also plotted onto the graph, showing the sensor working.
Movement *XYZ* Test	This test shows the *GY-521* sensor fully wired up to the Arduino and programmed to receive the movement on the *X*, *Y*, and *Z* axes. This is between a scale of −5 V to +5 V and is plotted onto a graph to show that it easily works and that each axis changes depending on the movement of the sensor. This is so that in robotic applications, the robot can be moved along these axes with ease.
Flex (added the second) test	This test just shows the second flex sensor being added to the project, allowing for a pinch motion to be made to open and close a claw, for example, on a robotic application.
Distance test (on the glove)	On this test, all the hardware has been installed onto the glove, and in the test, it shows that when the glove gets close to an object, the plot chart increases and decreases depending on the distance. In a robotic application, this feature can be used to show the robot how close it is to an object and instruct it on how to act accordingly.
Flex test (on glove)	These tests show both flex sensors working on the glove, including showing the plot chart for each of them as they increase and decrease. When used with robotic applications, this data can signify whether to open or close a claw on the system to hold an object, for example.

Table 1. *Cont.*

Test Type	Outcomes
Movement XYZ test (on the glove)	This test, shows how the *GY-521* sensor is on the glove; it works efficiently when moving along the *X*, *Y*, and *Z* axes, showing this on the plotted chart when the user moves their hand accordingly. This works great towards robotics applications as this allows for actual movement of the robot, allowing it to go along the *X*, *Y*, or *Z* axis
Output tests	This first test displays the output of the gloves and the data being output. The second test shows the plotting test of all the sensors working together, which is shown here in **Figure 8**. This figure shows a screenshot of the Live Plotting chart, as all the sensors are used to show that they work. As discussed, each sensor keeps to a value between −5 V and +5 V, as shown here when the sensors reach their minimum and maximum values. Also, each color line here represents a different sensor and value as shown in the keys above (Blue being the Flex Value from the flex sensor, Orange being the Object detection value from the Ultrasonic sensor, Green being the *X*-axis, Yellow being the *Y*-axis, and Pink being the *Z*-axis, all from the *GY-521* sensor).
Completed Glove tests (with and without battery)	These tests show the glove fully working, plugged in and battery operated. In the first test, you can see all the sensors working together on the plot chart. Then, the second test shows the glove battery operated and shows it working by the LED lights on the bath, showing the flex sensors working.
Live Plotting Tests	In these tests, the sensors were tested multiple times to show that they could be integrated with a robotic claw, for example, to open and close. Details of these tests are reported in the text.

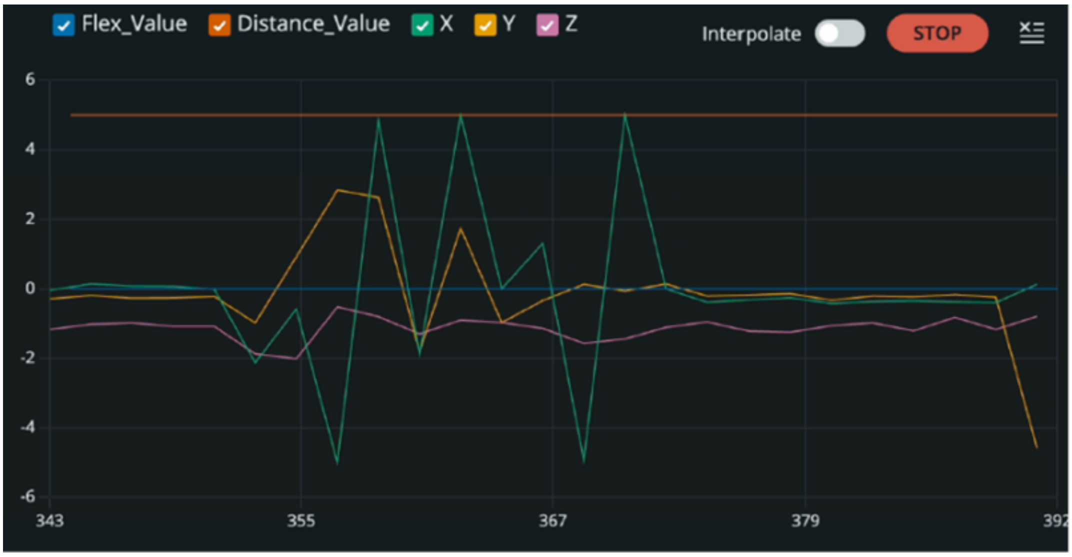

Figure 8. Plotting tests reporting the values of the flex sensors, distance, and accelerations according to the legend on the top left corner of the graph.

Table 1 summarizes the main setup of all the tests. A few more words need to be spent on the live plotting tests, where we explored a different set of scenarios, namely:

- **Flex Test Plotting:** In this test, both flex sensors were tested four times at each stage of flex to show that they both work and can be integrated with a robotic claw, for example, to open and close it at set stages depending on how much they are being flexed. As shown in this video, both Flex sensors-located on the two fingers, namely the thumb and the index-have been programmed to flex at two different positions, so when the finger is bent to about half, the value of each sensor will appear as 1, therefore showing on the plot chart, then when the finger is fully flexed this sets the value to 2 as shown in the test Aswell this comes out to be very accurate.
- **Object Detection Test Plotting:** In this test, the Ultrasonic sensor is being tested for object detection/distance detection. This is done four times as well to prove that it accurately outputs the correct value. In the program, it is set that when the glove is placed down on the table, the value is +5 V (being the closest to an object), and as the glove is pulled away from the table, the value decreases to show the distance it is being moved away from an object (maximum being five and minimum being 0 here).
- **GY-521 Test Plotting:** With the *GY-521* sensor, three tests were done to show that all three axes (*X*, *Y*, *Z*) were

detected when the glove was being moved. So, in each test, the glove is moved along each axis five times to accurately show on the plotting chart that the sensor is working accordingly and efficiently, and all three tests do show this. With this test, the sensor's values are set to a maximum of +5 V and a minimum of −5 V, so as shown in the tests, each movement that was done on each axis spikes between these values. Where in this case, in robotic applications, when the glove outputs these certain values, these can be outputted to the robot to tell it to travel along a certain axis to get to a set destination.

3.2. Outcomes

This project was successfully implemented and validated through a series of full experiments that showcased the functionality of each sensor, both individually and together. The initial tests focused on the ultrasonic sensor, which was tasked with measuring distances between the glove and surrounding objects. The results indicated that the ultrasonic sensor reliably detected distances within a range of 0 to 5 units, producing accurate output that confirmed its effectiveness for proximity detection and obstacle avoidance in robotic applications. This capability is critical in environments where safety and navigation are important, such as autonomous robotic systems operating in dynamic settings.

Next, the flex sensors were evaluated both independently and in a combined setup to understand their performance better. Each flex sensor was subjected to rigorous testing to accurately measure the degree to which the finger was bent. The data collected was then plotted to confirm the sensors' responsiveness and range, demonstrating their ability to accurately capture subtle movements. When integrated into the glove, the flex sensors effectively allow for simulated robotic gripper movements. This feature showcases their potential to control robotic mechanisms requiring fine manipulation, such as gripping and releasing various objects. Such functionality is particularly beneficial in applications that require precision, such as robotic surgery or assembly tasks in manufacturing environments. The *GY-521* accelerometer was also subjected to testing to assess its capability to measure movement along the X, Y, and Z axes. The accelerometer performed as expected, providing output in the range of −5 V to +5 V. When mounted on the glove, the accelerometer maintained its effectiveness, indicating that the glove could successfully capture and replicate the user's hand movements in three dimensions. This feature is crucial for robotic applications that require precise positioning and movement control, enabling a seamless transition from human actions to robotic responses. The final tests conducted involved the integration of all sensors and included scenarios where the glove operated on battery power. These tests confirmed the overall integration and functionality of the system. The plotted data clearly demonstrated that all components worked together harmoniously when powered by both a direct connection and a battery. This adaptability is vital for the portability and flexibility required in various robotic environments, enabling the glove to be used in diverse applications without being tethered to a power source.

In addition to validating the individual functionalities of the sensors, the tests also provided insights into the glove's overall performance and usability. Feedback during the testing process highlighted the glove's comfort and ease of use, which are essential factors for ensuring that the technology can be adopted effectively. This glove would be intuitive, enabling full control of robotic systems with minimal training. This aspect highlights the glove's potential to enhance user interaction with robotics, making it accessible to individuals without technical backgrounds. Moreover, some more testing could be done to show the integration of the glove with various robotic platforms so that it can demonstrate accuracy. This could include controlling robotic arms and other mechanisms with hand gestures, which would highlight the glove's versatility. The ability to translate natural hand movements into robotic commands opens exciting possibilities for applications in fields such as healthcare, where it can assist in inpatient rehabilitation, or in industrial settings, where it can enhance operational efficiency.

The successful outcomes of these tests indicate that the sensors can be effectively used for real-time motion capture, object detection, and interactive control. This showcases the glove's potential for practical use in robotics and suggests a promising future for further development. The results provide a solid foundation for future improvements and enhancements, which could include the addition of more advanced sensors, improved software algorithms for gesture recognition, and greater integration with complex robotic systems. In summary, the experiments conducted during this project have provided strong evidence that the glove system is fully operational and capable of being integrated into robotic applications. The validation of each sensor's functionality and the successful integration of all components point to the glove's ability to facilitate intuitive human-robot interaction. The promising results achieved through this project open the door for future research and development, potentially leading to more sophisticated and user-friendly robotic control systems that can be applied across various industries.

3.3. Applications

At this stage of the project, we have not applied the proposed design into a specific experimental protocol, enhancing biomimetic applications of the system. Nevertheless, it is useful to foresee applications where the glove could be used as a user-friendly interface for any type of application, such as sign-language translation [15], speech synthesizer [16], or motor learning studies [17]. In this context, it is also worth mentioning how this type of device could support rehabilitation tasks, human motor recovery, and, more simply, the acquisition of the inter-phalangeal movements, namely the capturing of human hand synergies (see for example, chapter 4 of the studies [18, 19]). Therefore, it is important to emphasize how low-cost devices, which are properly designed, provide a miscellaneous of applications and improve end-user experience in a variety of applications.

4. Discussion

This section focuses on the main advantages of the system and its limitations.

4.1. Strengths

The *glove-based control system* developed for robotic applications has several strengths that make it an effective and versatile tool. Firstly, the combination of multiple sensors, including an ultrasonic sensor, flex sensors, and an accelerometer (*GY-521*), allows the glove to capture a wide range of data. This setup makes it possible to control robotic movements based on hand gestures and motions. Each sensor plays a specific role: the ultrasonic sensor measures distance, the flex sensors detect finger movements, and the accelerometer tracks the position and motion of the hand. Together, they create a powerful and flexible control system that can be applied in different areas, such as industrial robotics, healthcare, or assistive devices. Another major strength is the accuracy and reliability of the sensors. During testing, the ultrasonic sensor consistently measured distances accurately, which is crucial for robotics applications where the robot needs to detect obstacles or know how close objects are.

The *flex sensors* accurately picked up finger bending, allowing for precise control, like opening and closing a robotic gripper. The *accelerometer* was also able to capture the movement of the hand across all three axes (*X*, *Y*, and *Z*) with good precision. This level of accuracy shows that the glove could be used for fine-tuned control, which is essential for tasks that require careful manipulation, like picking up small or delicate objects.

The *modular design* of the glove is another advantage. The sensors are set up in such a way that they can be removed or replaced individually without affecting the rest of the system. This means that if new sensors become available, they can be easily added or swapped out. This flexibility makes it easier to upgrade the glove in the future, ensuring it remains adaptable for various needs and technologies. For example, adding pressure sensors or temperature sensors could further increase the glove's functionality. *Portability* and ease of use are also key strengths. The glove is designed to fit comfortably and operate without needing to hold any additional devices, making it hands-free and easy to use. It can also be powered by a battery, allowing it to be used in different locations without needing to be plugged in. This is especially useful in situations like search and rescue, where mobility and convenience are important.

Finally, the *software* and *hardware* work well together, which is essential for a functioning system. The Arduino platform was chosen for its simplicity and accessibility, making it easy to program and modify as needed. The code successfully collects and processes the sensor data, showing that the glove could be integrated with more advanced technology, like machine learning, to make it even more accurate and responsive in the future.

4.2. Weaknesses and Potential Improvements

Despite its strengths, the glove system has some weaknesses that could be addressed to make it even better. One of the main issues is the need for accurate *calibration* of the sensors, particularly the accelerometer. The accelerometer needs to be calibrated manually to adjust for small errors (called offsets), which can take time and may not always be done correctly. If the calibration is not perfect, the data from the accelerometer may not be accurate. To solve this, future versions could use automatic calibration algorithms that would automatically adjust the sensors when the glove is first turned on. This would make setup quicker and reduce the chance of errors. Although this glove does include a small automatic calibration program at the start, it can sometimes be quite slow. Therefore, a more efficient and large-scale automatic calibration could be implemented as discussed. Another issue is the *noise* and *interference* that can affect the flex sensors. Flex sensors can sometimes pick up interference from other electronic devices or environmental conditions, causing them to give inaccurate readings. To fix this, future versions of the glove could use signal filtering algorithms to clean up the data and make it more accurate. Additionally, using higher-quality flex sensors and better shielding for the wiring could reduce the amount of interference the sensors pick up.

Battery life is another area that needs improvement. While the glove can run on battery power, adding more sensors increases the power usage, meaning the battery does not last as long. To fix this, future versions could use more efficient sensors and optimise the code so that the glove enters a low-power state when it is not in use. This would extend the battery life. Alternatively, adding a larger rechargeable battery or even a small solar panel could provide more power for longer periods, especially for outdoor or remote use. Another challenge is *scalability* and *integration* with more advanced robotic systems. While the glove works well for simple tasks like moving a robotic arm or opening and closing a claw, it might need to be upgraded for use with more complex robots. For example, industrial robots that operate in factories often have multiple joints and more complicated movements, which would require the glove to be even more precise. To address this, future improvements could involve developing more advanced software that uses machine learning to recognise more complex hand gestures and movements [20,21]. This would allow the glove to control more sophisticated robotic actions, making it suitable for a wider range of applications.

Finally, the *comfort* and *durability* of the glove could be improved. Since the glove needs to be worn for long periods, it is important that it fits comfortably and does not feel too heavy or restrictive. However, with multiple sensors and components attached, the glove can become bulky. Additionally, the materials used must be durable enough to withstand regular use, particularly in demanding environments like factories. To overcome these challenges, future designs could use flexible and lightweight materials, like flexible printed circuit boards (PCBs), that would make the glove feel more like a natural part of the hand. This would not only make it more comfortable to wear but also increase its durability and ease of use.

Overall, the glove-based control system has a lot of potential but still has areas for improvement. By addressing these weaknesses, such as automating calibration, reducing noise in sensor data, extending battery life, enhancing comfort, and increasing compatibility with more advanced robotic systems, the glove could become a powerful and reliable tool for a wide range of robotic applications.

5. Conclusions

This project successfully developed a glove-based control system for robotic applications, drawing on insights gained from a comprehensive literature review. The review highlighted the potential of *wearable technology* to improve interactions between humans and robots. By examining existing technologies and methods, a solid plan was created for combining various sensors, specifically, an ultrasonic sensor, flex sensors, and a GY-521 accelerometer, into a glove design capable of effectively controlling robotic movements.

The methodology for this project involved several key steps: designing, prototyping, and testing the glove system. This systematic approach allowed for careful selection and integration of each component, ensuring that their performance could be assessed both individually and collectively as part of the system. During the development phase, a focus was placed on making the glove comfortable to wear while ensuring it could effectively control robots. The design process was made, allowing for adjustments based on testing results. The aim was to achieve a modular setup where sensors could be independently assessed for performance and then integrated into the glove design. This approach helped with thorough testing and ensured that any potential issues could be isolated and addressed without disrupting the entire system.

A series of tests was conducted to evaluate the glove's functionality. The *ultrasonic sensor* performed well, accurately detecting distances within a range of 0 to 5 units. This capability is essential for helping robots avoid obstacles and understand their surroundings. The ability to measure proximity with precision opens applications in navigation and object interaction, which are critical for robots operating in complex environments. The *flex sensors* also worked well as they effectively tracked finger movements, enabling precise control of robotic grippers.

This feature is particularly useful for tasks requiring careful handling, such as picking up and releasing objects. By integrating flex sensors into the glove, it was shown that the glove could simulate the actions of a human hand, providing a more intuitive way to control robotic mechanisms. Furthermore, the *GY-521 accelerometer* worked reliably, capturing hand movements across three axes, crucial for applications demanding accurate positioning and movement control. This three-axis functionality allows the glove to replicate complex gestures, enabling more sophisticated interactions with robotic systems. Final tests confirmed that the entire system could function effectively when powered by both a direct connection and a battery. This adaptability enhances the glove's portability, making it suitable for various environments, such as industrial settings or search and rescue missions. By ensuring that the glove can operate independently of a power source, its usability in real-world scenarios where power availability may be limited is increased.

The *glove-based control system* boasts numerous strengths, making it an effective tool for robotic applications. Firstly, the integration of multiple sensors enables the collection of diverse data, allowing the glove to respond accurately to hand gestures and motions. Each sensor plays a specific role: the ultrasonic sensor measures distance, the flex sensors detect finger movements, and the accelerometer tracks hand motion. Together, they create a powerful control system applicable in various fields, including industrial robotics, healthcare, and assistive devices. Another major strength is the *accuracy* and *reliability* of the sensors. Throughout testing, the ultrasonic sensor consistently measured distances accurately, which is crucial for robotics applications where proximity detection is essential. The flex sensors effectively captured finger bending, allowing for precise control of robotic grippers. The accelerometer accurately captured hand movement across all three axes, demonstrating the glove's potential for fine-tuned control in delicate tasks.

Despite these strengths, several limitations were identified during testing. One challenge is the need for accurate calibration of the sensors, especially the accelerometer. Manual *calibration* can be time-consuming and may not always yield perfect results. Future versions could benefit from automatic calibration algorithms that streamline the setup process and reduce potential errors. While a basic automatic calibration feature was included, its slow execution highlighted the need for a more efficient and comprehensive approach. *Interference* affecting the flex sensors was another concern, as they can sometimes return inaccurate readings due to external electronic noise or environmental factors. Implementing signal filtering techniques in future designs could help lessen these issues. Additionally, using higher-quality flex sensors and improved shielding for wiring would reduce the risk of interference. *Battery life* is also an area needing improvement. While the glove operates on battery power, the addition of more sensors increases power consumption, leading to shorter battery life. Future iterations could incorporate more energy-efficient sensors and optimise the code to enable a low-power state when the glove is not in use. Exploring options for larger rechargeable batteries or integrating small solar panels could provide more extended power, especially for outdoor or remote applications.

To further enhance the glove system, several improvements could be made. Firstly, automating the calibration process for the accelerometer and flex sensors could streamline the initial setup, making the glove more user-friendly and ensuring consistent performance across various environments. Implementing advanced signal filtering algorithms could improve the accuracy of flex sensor readings, reducing the impact of noise and interference. Further research into low-power components and battery optimisation techniques could extend the glove's operational life. Employing power management strategies to minimise energy consumption during periods of inactivity would be beneficial. Expanding the sensor array to integrate additional sensors, such as pressure or temperature sensors, could enhance the glove's functionality. These sensors could provide additional data points, making the glove suitable for more complex tasks in robotics [20].

Future designs should also prioritise the glove's comfort and durability. Exploring lightweight materials and ergonomic designs could make the glove more comfortable for extended wear, while enhancing durability would ensure it can withstand the rigours of regular use in various environments. Improving software algorithms to recognise complex hand gestures and movements would allow for more sophisticated control of robotic systems. Implementing machine learning techniques could facilitate the glove's adaptation to individual users' gestures, making it more *intuitive* and *user-friendly* [22,23].

Finally, developing the glove to work seamlessly with more advanced robotic systems could expand its range of applications. Ensuring compatibility with existing robotic platforms and exploring ways to enable multi-robot cooperation could significantly enhance its utility. In conclusion, the glove-based control system has great effectiveness for real-time motion capture, object detection, and interactive control in robotics. By addressing the identified weaknesses, such as improving calibration, reducing sensor noise, extending battery life, enhancing comfort, and increasing compatibility with advanced robotic systems, the glove could become a powerful and reliable tool for various robotic applications. Overall, this project represents a meaningful step forward in advancing human-robot interaction and opens the door for further research and development in this exciting field.

Supplementary Materials

The following links provide a list of video demonstrations of the working principles of the system:

1. Distance test
   Link: https://youtube.com/shorts/CnNVhYDpVqg
2. Flex test
   Link: https://youtube.com/shorts/AD0oHC57Uyk?feature=share
3. Movement *XYZ* test
   Link: https://youtube.com/shorts/50iYmbujeD8?feature=share
4. Output tests
   Link: https://youtu.be/d7jNCdGLJuI
   Link: https://youtu.be/92u5P8xwz0c

Author Contributions

Conceptualization, H.L.; methodology, H.L.; software, H.L.; validation, H.L.; writing—original draft preparation, H.L. and E.L.S.; writing—review and editing, H.L. and E.L.S.; supervision, E.L.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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