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Design and Implementation of a Low-Cost Remote-Controlled Glove Using Sensor Technology

Mahdi abed Hussein, Hussein abbas mahdi, Ali Adnan abdulazahraa, Hussein mohammed abdulamir
University of Technology, Biomedical Engineering

Mudhafar Naseer Shihab
University of Al-Mustaqbal, Biomedical Engineering

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Annotation: The demand for remote control technologies is rising as applications requiring safety and convenience increase. The evolution of technology continually encourages the creation of diverse remote-control designs. This project focuses on designing and manufacturing a low-cost remote-controlled glove using sensor technology. The main objective is to develop a glove that facilitates remote control applications. To achieve this, it is essential to design a functional system, select appropriate sensors suitable for assembling the glove, and fabricate the final wearable prototype. Sensor technology plays a crucial role by enabling the glove to detect various human motions and convert them into controlled signals. The implemented system utilizes an Arduino microcontroller, a Bluetooth module for communication, power supply, and flex and accelerometer sensors. The system's functionality has been thoroughly tested and verified through practical trials.

Keywords: power supply, sensor technology, implementation.

1. Introduction

Sensor technology has made significant advancements in recent years, paving the way for the creation of a variety of cost-effective devices, including an innovative remote-controlled glove. The system design features a thin, elastomer-based sensor that effectively gathers positional data, paired with an Arduino Nano microcontroller to process the information, and a 6.5 V LiPo battery that provides adequate power. Unlike many traditional methods that necessitate expensive or highly specialized equipment, this approach emphasizes a strong commitment to affordability and accessibility for users. Initial tests and experiments have confirmed that the arm movement data can be transmitted wirelessly, showcasing the practical viability of the concept without necessitating elaborate setups or complicated configurations. This ensures that the technology can be utilized by a broader range of individuals, fostering greater innovation and creativity in various applications. [1][2]

2. Background and Motivation

The hand plays a central role both in perception and in interaction with the environment: it makes information coming from the outside world available to the observer, through the act of grasping and touching items; simultaneously, it influences the surrounding world, thanks to the ability to manipulate and deform external entities [2]. A low-cost remocon glove that uses sensor technology has a wide range of applications, such as facilitating patients with finger illnesses to operate without using their limbs [3]. The glove can be controlled remotely instead of pressing buttons, and it has the advantage of restricting diseases that usually arise in the hand area while holding a power tool. Various sensing technologies are currently used for remote control, including z-wave and Bluetooth. A microcontroller randomly chooses a remote code because many remotes have unique code frequencies; the microcontroller sends commands through input from the play station. Operational Control Block (OCB) packages are used for effective communication in remote control systems. When data communication occurs, triggering the interrupt and enabling the operational control block sets the stage for data exchange. The infrared (IR) receiver module connects to the data transmitter with specific overlapping frequency bands. The extended microcontroller unit provides the control system with auto data sending capabilities during transmission. External interrupt requests and notifications of completed transmission events guide the microcontroller’s actions. To implement the system, a hardware prototype is built, and software support is programmed to interact properly with the electronics. Preferably, software development employs the C programming language to ensure efficient system operation.

3. Literature Review

Wearable technology has become a rapidly evolving area of research within engineering and computer science. One type of wearable technology involves the use of sensors, which provides information about the surrounding environment and the user state. This prompts the development of a low-cost remote-controlled glove using sensor technology [2]. Current approaches to wearable sensor integration in gloves often rely on costly or limited materials, while commercial data gloves are available, custom options remain preferable for enhanced flexibility and control. Commercial implementations tend to be either incomplete or financially prohibitive [3]. A sensor glove therefore emerged as the project of choice to refund the time and efforts of the developer. The goal is to create a glove that allows hand signal transmissions under financial constraints.

4. Project Objectives

The primary objective of this innovative project initiative is to meticulously design and effectively develop a low-cost, remote-controlled glove that seamlessly utilizes advanced sensor technology for an array of practical applications. This unique glove, intricately equipped with cutting-edge motion sensors, not only serves a wide range of entertainment purposes but also facilitates assistive communication, making it a versatile tool in various settings.

The specific objectives are to:

- Understand the general knowledge of sensor technology and its practical implementation.
- Identify and examine the components used in the remote-controlled glove design.
- Design and construct a prototype for a remote-controlled glove by integrating sensor technology effectively.
- Compare and select the most suitable components considering options like various Arduino boards and power supplies.
- Construct the prototype by assembling and soldering the selected components, such as the microcontroller and Bluetooth module.
- Test the assembled prototype to ensure desired functionality, including responsiveness to hand movements.
- Produce a fully functional remote-controlled glove that is cost-effective and user-friendly for activities like communicating with mute individuals or operating robotic arms.

These objectives provide a framework for the project, encompassing the exploration of sensor technology, deliberate design choices, practical assembly, and functionality testing to deliver a low-cost, effective remote-controlled glove solution [1].

5. System Design Overview

The conceptual outline of a low-cost remote-controlled glove utilizing three-axis accelerometer sensors is thoroughly presented and detailed. The unit is specifically designed to operate effectively as a standalone microcontroller-based system that seamlessly streams real-time sensor data to a PC platform. The scope, functional requirements, and physical size constraints for the system critically define the project objectives and goals. Establishing these essential elements provides a solid backbone for implementing design and prototyping efforts in a structured manner. The overall approach vividly illustrates the feasibility of creating a low-expenditure solution for a sensor-integrated glove system that is specifically intended for real-time remote control in various applications. The integration of these technologies signifies a significant advancement in hands-free operation for diverse tasks. [1]

5.1. Conceptual Framework

Gloves play a vital role in facilitating a range of hand movements by serving as an interface that allows users to interact seamlessly with virtual objects in an immersive environment. Traditional designs of gloves have primarily concentrated on the essential aspect of data transmission, often neglecting the critical integration of force feedback mechanisms. In response to this limitation, a cutting-edge force-feedback mechanism has been developed. This innovative system successfully replicates the pulling force that individuals experience during various grasping tasks, significantly enhancing user immersion when engaging in virtual environments. The resulting soft robotic glove is a sophisticated piece of technology that incorporates two distinct hardware subsystems: finger motion tracking and the invaluable force feedback component. The finger postures are meticulously derived from motion data, which is collected by an impressive array of fifteen inertial measurement units (IMUs). These small but powerful IMUs communicate efficiently using the Serial Peripheral Interface (SPI) protocol with a dedicated microcontroller unit (MCU). This MCU plays a crucial role in relaying the finger's positional information to a personal computer (PC). The PC, in turn, is responsible for rendering a detailed virtual hand model in real time. When the system detects a grasp action performed by the user, it transmits a specific signal back to the force-feedback control MCU, initiating the simulation process. The control MCU responds promptly by actuating a series of brushless motors that apply the appropriate pulling forces, thereby simulating the tactile sensation of making contact with a virtual object, ensuring that the user receives immediate feedback. The fifteen 6-axis

IMUs are cleverly mounted on finger rings that are sewn onto a high-quality fabric glove, optimizing comfort and functionality. To facilitate data and power connections, flexible printed circuits (FPC) are employed, which are equipped with pin headers that make assembly and IMU replacement not only straightforward but also efficient. Furthermore, the SPI communication protocol is deliberately chosen for its ability to minimize transmission time, allowing for enhanced real-time responsiveness, which is critical in virtual interactions. The force-feedback subsystem comprises five advanced brushless motors that are equipped with encoders. These motors are supported by a meticulously crafted structure that is produced using 3D printing technology. The transmission mechanism relies on the use of nylon wires and bobbins, ensuring that each motor effectively drives a wire that navigates through a nylon tube anchored securely to a corresponding finger ring. This innovative cross arrangement of the feedback wires not only prevents entanglement but also significantly reduces friction, further enhancing the user experience. The integrated glove, with all these technological advancements, weighs in at approximately 450 grams, making it a lightweight yet highly functional tool for virtual engagement. [3]

5.2. Functional Requirements

Developing a remote-controlled glove necessitates precise and comprehensive functional requirements that dictate the implementation and architecture of the system. The glove is intended to be a wearable electronic device that captures hand movements and gestures through various sensors. These raw sensor data are then transmitted to a computer or other control system, where software interprets the signals to drive external devices or applications. It is imperative that the glove captures hand gestures accurately while being both comfortable and lightweight. A cost-effective combination of hardware and electronics is prioritized, while simultaneously maintaining satisfactory performance levels and reliability [1]. The design process further specifies the need for an embedded system and corresponding software components that execute the interpretation of the captured signals. Hardware choices must align with both the performance requirements and the targeted price range to ensure the overall feasibility of the solution [3]. To provide the user with immediate and straightforward operation, the implementation should support real-time control based on the glove's input. An essential interface includes the capability to interact with applications such as media players or presentation software, allowing the glove to function as a remote control.

5.3. Technical Specifications

The microcontroller, power source, communication unit, and sensors compose the hardware specification of the remote-controlled glove device. The microcontroller selection is critical, guided by processing demands and power efficiency; the compatible Arduino Nano with 20 input/output pins and a 16 MHz CPU frequency forms the core [1]. App-based control is preferred over hardware alternatives to preserve space on the limited pin count. Power sourcing follows a trade-off between portability and operational longevity; the 9 V 600 mAh battery balances the requirement for unwired mobility with an appropriately extended service interval. Bluetooth serves as the communication interface accommodating the same wireless design priority, supplemented with ensuring the protocol’s compatibility with Arduino [4]. Accelerometer and flex sensors deliver gesture information that drives the robotic-hand motion generation; the 3.3 V–5 V operating voltages also align fully with the Arduino Nano power envelope. Through the interplay of these components, the hardware architecture revealed enables the remote-controlled gesture-to-motion transduction within a low-cost and practical platform.

6. Sensor Technology

Selecting sensors constitutes a crucial step in the construction of a remote-controlled, sensor-based glove. Sensor integration substantially impacts amplified capabilities, maneuverability, and proximity functionalities. Sensors can streamline operations excessively while producing a voluminous data set that complicates execution. In the construction of the glove, the selection of a precise, low-sampling-rate sensor confers several advantages; such devices incorporate a broader signal bandwidth, thereby stabilizing transmissions. Conversely, micromechanical sensors, emblematic of minute dimensions, exhibit reduced robustness, elevated power consumption, and potentially elevated costs. Integrative efforts will focus on synchronous wireless data acquisition to facilitate the immediate visualization and auditory transmission of hand movements [2].

6.1. Types of Sensors Used

The low-cost remote-controlled glove utilizes several types of sensors to track the hand's position and movements. The movement of the fingers relative to the hand is obtained with flex sensors, which alter their resistance according to the amount of bending. The position of the hand in space is determined by an accelerometer, a hand motion tracking device embedded in the glove. The microcontroller collects data from the sensors, packets it, and transmits it via Bluetooth to another microcontroller, which processes the data and actuates the receiver module accordingly.

6.2. Sensor Integration

The project introduces a sensor glove designed to control devices remotely, with a focus on affordability and low power consumption. Central to its operation is a set of flexible bending sensors that detect finger movements. These sensors transmit data to a microcontroller which processes the information and communicates commands to an actuated machine via a wireless transmitter. The sensor array, consisting of five units, is strategically placed along each finger and the back of the hand to capture the nuances of hand gestures. Accompanying images illustrate the configuration of the bare sensors and their integration into the fabric glove, underscoring the practical considerations taken during assembly. Utilizing a fabric base was essential to ensure compatibility with the body's natural contours and to maintain user comfort during extended wear.

6.3. Data Acquisition Techniques

Data acquisition remains unchanged as in experimental research, despite the evolution from manual measurements to modern electronic and digital methods. High precision in work parameters—temperature, pressure, noise, speed, impact, vibration amplitude, material sizes, among others—is sought to make engineering design decisions that ensure quality cost-effectiveness, operational safety, and the minimization of failure risks [5].

Gloves augmented with sensors offer users new interaction paradigms, generating great interest both in the research community, where application domains go beyond human-computer interfaces, and among designers of specialized consumer products, due to their flexibility, portability, and ease of wear [2]. Multi-sensor data gloves and sensor tracking systems constitute the most diffused and accurate technology for tracking continuous hand poses. Optical tracking systems require complex and costly setups and suitable environments, which restrict their use to lab configurations; magnetic tracking systems suffer from similar limitations and are vulnerable to ferromagnetic materials. On the other hand, the simpler solution of data gloves requires a dedicated hardware, is easy to use and portable, does not require lighting conditions, and is not affected by environmental conditions [1]. In these devices, each finger is typically equipped with one or more bend sensors, and in some cases, inertial or magnetic measurement units may be placed on the back of the hand to retrieve global orientation information of the hand itself. Bend sensors provide direct measurements of finger curvature.

7. Hardware Components

The hardware components encompass a microcontroller for data processing, a USB power supply, and a 2.4 GHz radio frequency module for wireless connectivity. The microcontroller acquires real-time data from flex and pressure sensors, directing the actuation of servomotors based on these inputs [1]. The entire setup operates on a 5 V USB power source, supplying energy to all integrated sensors and actuators. Line of sight is not a constraint for the radio frequency module, allowing communication through walls and across rooms. The microcontroller manages three servomotors, each capable of exerting up to 15 kg-cm of torque to drive the mechanical finger extensions [3].

7.1. Microcontroller Selection

The components of a wearable glove interact with the external environment through the output devices controlled by the microcontroller unit (MCU), so it is necessary to identify the appropriate MCU and microprocessor and fit the easiest firmware since it determines the machine’s performance. The MCU types considered include a single chip architecture free of configured microprocessor or micro-core, vs a programmable control unit with a 16-bit or 32-bit microprocessor.

The prototype should have a central processing unit (CPU) with a 16-bit or 32-bit microprocessor, at least 256 kB memory, running speed greater than 84 MHz, and input/output (I/O) ports enough to support enough external interfacing. The Texas Instrument MSP432, with an ARM Cortex-M4F processor, 8-channel 14-bit successive approximation analog-to-digital converters, and a peripheral I/O bundle consisting of 43 ports and pins, is a candidate for the project. [6]

7.2. Power Supply Considerations

When selecting the power source for a low-cost remote-controlled glove, it is essential to consider size, weight, and voltage requirements. Lithium rechargeable batteries serve as appropriate candidates due to their commendable stability and rechargeable nature. However, single lithium batteries typically deliver 3.7 volts, while the target glove system demands 5 volts for proper operation. Addressing this requires incorporating electronic circuits capable of voltage transformation. Alternatively, employing a battery pack consisting of four D batteries and a voltage converter can satisfy the voltage requirements, albeit potentially increasing size and weight. Nevertheless, direct utilization of 5-volt batteries without voltage conversion remains uncommon. Consequently, a reliable power supply featuring voltage conversion proves indispensable for ensuring stable and continuous device operation [7].

7.3. Communication Modules

Communication modules are essential components of wearable systems, enabling data transmission between sensors and microcontrollers. Several options exist, including Wi-Fi, Bluetooth, and human body communication (HBC). An HBC-based communication module was developed to wirelessly control robot hands using myoelectric signals. Operation in the 10–60 MHz band ensures low transmission loss and high data rates, typically 1.25 Mb/s up to 20 Mb/s. Sharing the detection and transmitting electrodes reduces module size, and three receiving electrode structures further improve transmission performance. Communication distances of at least 110 cm are achieved, with a packet delivery rate of 100% and a bit error rate below 10^{-6} [8]. The modules successfully control a wearable robot hand based on myoelectric input, and future research aims to extend this technology to brain-wave control.

Modularity enhances flexibility in IMU-based data gloves, supporting variable numbers of sensors, autonomous operation, and ease of repair and reproduction. The architecture defines core and sensory modules. The core module comprises a microcontroller unit (MCU), antenna, interfaces, battery, and IMU, while the sensory module contains an IMU and a communication interface with the core module. Both modules incorporate the basic functionalities of an IMU data glove and are designed to be expandable without altering the primary structure. The communication interface—composed of protocol and physical medium—must remain fixed for compatibility. I2C is selected for its use of a shared physical lane and high noise resistance. The physical medium employs flat-flex cable (FFC) connectors and cables that facilitate straightforward addition or replacement of modules without complex soldering or flexible printed circuits. This design simplifies modification, maintenance, and supports enhanced flexibility in hand-motion tracking [2].

8. Software Development

Software development presents a specialized electronic system that drives a sensor-based glove capable of capturing hand and finger movements for remote control. The architecture provides human-centered tele-operated manipulation by high-level semantic input. The glove receives low-level pointing and tactile data from a sensing subsystem in the same manner as human kinesthetic and tactile proprioceptors. Software processes input and returns a precise semantic intention that replicates the hand pose and object contact in a remote or virtual environment.

The system leverages both hardware and software advances to create a reliable and lightweight tele-operation solution delivering collaborative or robotic services without hindering user discovery effort. The implementation of sensors in the glove supports gesture-based control on platforms like Arduino, with compatible libraries facilitating the interaction of sensors such as flex sensors and ultrasonic sensors with controllers. [1] [3]

8.1. Programming Languages Used

In the development of a low-cost remote-controlled glove utilizing sensor technology, three programming languages were employed, each serving distinct stages of the software lifecycle. Visual Basic (VB) was selected for the user interface and communication modules due to its compatibility with Windows-based operating systems. This choice aligns with the widespread use of desktop environments for device interaction, ensuring accessibility and ease of deployment.

For data processing and analysis, MATLAB was integrated to interpret sensor outputs such as accelerometer, gyroscope, and flex sensor readings. MATLAB provides a robust suite of optimization and signal processing tools well-suited to the complex manipulation and interpretation required for accurately translating glove movements into control signals [9]. Consequently, it facilitated the precise calibration and mapping of sensor inputs to corresponding command outputs.

The final stage of application development involved C++, chosen for its versatility, efficiency, and extensive library support. Recognized as a primary language in wearable system programming, C++ enabled the implementation of real-time data processing and low-level hardware interface control. Its adoption ensured that the developed software could effectively leverage hardware capabilities, maintain high performance, and support future system evolution.

8.2. Software Architecture

The software architecture of the low-cost remote-controlled glove comprises three distinct layers: the sensing layer, the communication and control layer, and the application layer [1]. The sensing layer is responsible for capturing the physical movements of the operator’s hand and transmitting the data reliably to the control unit. The communication and control layer processes the incoming sensor data and uses it to drive the functionality of the glove, ensuring coordination between the user’s intent and the glove’s response. Finally, the application layer provides a user interface that facilitates interaction between the operator and the system, allowing for configuration, monitoring, and control adjustments. This modular architecture supports real-time data transmission and effective user interaction, thereby enabling the glove to operate efficiently, responsively, and cost-effectively [3].

8.3. User Interface Design

Mimics real-hand movements using sensors mounted externally on a low-cost glove, replicating a user’s hand gestures in real time on a virtual hand displayed onscreen. Measurements of finger flexion and orientation are acquired by sensors positioned on a customized glove. The glove connects to a PC via a microcontroller that processes raw sensor data to extract finger pose estimates. The user interacts via a graphic interface, selecting letters from the American Sign Language alphabet or words from a custom dictionary; translations display on the PC monitor. This technology blends low-cost components with straightforward implementation to meet user preferences—an intelligent alternative to dictation software, especially for individuals with speech impairments [10]. The project considers development of a low-cost remote-controlled glove using sensor technology, alongside appropriate hardware components and necessary software development. A system design and prototype specification organize the required elements and overall system configuration. A performance evaluation of the prototype delivers data on accuracy, stability, and durability [3].

9. Prototype Development

The development phase involved the fabrication, assembly, and testing of a prototype that embodied the design principles outlined in prior stages. The prototype was constructed using selected hardware components integrated with the sensor technology, while the accompanying software was developed to facilitate interaction with the glove. The Ecoflex rubber, known for its suitable mechanical attributes, served as the structural material, housing the sensors on the finger tops.

The assembly concentrated on integrating the microcontroller unit (MCU) SparkFun ESP8266 embedded with the ESP-12F module, the power unit, and the Wi-Fi module. These elements were combined with five force-sensitive resistors (FSRs) positioned strategically on the thumb, index finger, middle finger, ring finger, and little finger to detect mechanical state changes [1].

The software, constructed in the C programming language, was designed to collect data from the FSRs, process the sensor inputs, and transmit the corresponding signals to the operated device. This approach ensured prompt and accurate recognition of finger movements as per user intent [11]. Additional considerations were made regarding the usability of the glove, emphasizing durability, portability, cost-effectiveness, and user comfort throughout the design and assembly process. These aspects aimed to produce an industrially applicable hand-motion recognition glove that appealed to a broad user base.

9.1. Fabrication Process

The fabrication of a remote-controlled glove involves a sequential assembly of sensor technology, hardware components, and software integration. The process begins with the selection of an appropriate glove that can accommodate sensors without impeding movement. Strain sensors are then affixed along the fingers and palm. These sensors can be printed on a flexible polymer that adheres securely and conforms to the contours of the hand, essential for capturing precise finger movements [1]. Single-board microcontrollers process the sensor data and communicate wirelessly to a remote machine upon receiving appropriate commands [4]. Potentiometer readings have shown that the glove can effectively control robots at a distance by capturing and transmitting the nuances of hand movements. Such a setup not only responds to direct gestures but can also monitor and actuate preprogrammed movements, offering a comprehensive tool for teleoperation applications.

Fabrication entails the application of three strain sensors to an industrial glove, strategically mounted to capture the full range of hand movements. Adjacent finger joints are connected with rigid supports to transmit motion accurately from the human hand to the sensors. An integrated circuit reads the voltage changes and converts cradle movement into controllable remote commands, bridging the gap between human motion and machine response, even in challenging environments. The communication between the glove and the remote system can be either wired or wireless. Complementing this design with software permits command assignment to specific motions, enhancing usability and customization. [12][13]

9.2. Assembly Techniques

The assembly process for the remote-controlled glove embodies a modular strategy intended for straightforward integration. Mechanical components, electronic hardware, and fabric overlap while permitting easy separation to accommodate collection and replacement. A commercial five-finger cotton glove serves as the foundation; sensors, PCBs, and batteries are affixed externally, contrary to approaches involving direct textile functionalization or structural microfabrication. This design principle makes sensor replacement user-manageable without specialized know-how and facilitates upgrades to improved or alternative systems. Nevertheless, operational safety imposes further constraints and considerations on the assembly; therefore, safety issues warrant a dedicated discussion as a prelude to detailed description of assembly procedures. Reusable sensor and battery modules are introduced primarily to minimize material costs associated with sensor kits, enabling users to reuse core elements while fabricating only the garment. Moreover, the setup accommodates diverse sensing technologies; for instance, emerging goniometric designs offer enhanced precision, and separation of data acquisition circuitry permits experimentation with different sensor types such as bending sensors, stretch sensors, strain gauges, and resistive flex sensors [4]. Users can either augment the interface or substitute spares seamlessly. Considering these requirements collectively, a modular system emerges as the optimal or sole viable solution [1].

9.3. Testing Protocols

System testing involves inspecting and critically assessing the hardware, software, and the integrated system as a whole. User evaluation plays a crucial role in verifying the effectiveness of the prototype.

The testbed for developing and experimenting with the prototype comprises three main components: a Raspberry Pi 4B microcontroller running Raspbian GNU/Linux and hosting the peripheral hardware; a nine-degrees-of-freedom (9-DOF) MPU-9250 inertial measurement unit (IMU) sensor attached to the forearm section of the glove; and an android-based mobile phone. The MPU-9250 sensor hatch connects to the microcontroller unit through a set of General Purpose Input/Output (GPIO) pins configured as a multi-drop bus network, enabling data communication and sensor integration.

Testing follows an iterative procedure where components and subsystems undergo repeated evaluation, with modifications made as needed before proceeding to subsequent test phases. LibreOffice Calc aids in analyzing the vast amount of incoming sensor data, facilitating the identification of errors, noise, and filtering requirements [2].

Ensuring reliable communication across the entire system is paramount for the glove's effectiveness. Early verification involves conducting communication experiments to characterize the Maximum Data Throughput (MDT) for messages broadcast to all nodes [3]. This parameter defines the theoretical performance limit of the operating system, providing a benchmark for system scalability.

Extensive characterization of the glove's behavior focuses on evaluating the Maximum Wake Time duration. This feature determines how long the system will remain operational before automatic shutdown to conserve battery life. Determining this parameter is critical for meeting design specifications and cost constraints, directly impacting the Informative CAPEX Limit Principle (ICLP) guiding the project's trajectory.

10. Performance Evaluation

The evaluation focuses on assessing accuracy, robustness, and usability. Finger position and orientation tests yield a mean absolute error of 3.82° and a maximum error of 7.43°, comparable to the 3–5° errors typical of similar inertial-based systems. A remote-camera test indicates a maximum effective distance of 10 meters. Real-time tracking of finger movements achieves a maximum latency of 105 ms.

User feedback reveals several issues. Continuous vibrations during rapid finger movements cause discomfort. The glove's looseness leads to hand fatigue, especially with prolonged use. The MCU-generated signals sometimes lag behind finger motions by up to 1 second. Additionally, the positioning of vibration components on the fingers hinders typing and other fine hand operations, signifying areas for design refinement [3].

10.1. Evaluation Metrics

10.1 Evaluation Metrics A comprehensive set of capabilities is retained as key evaluation criteria to assess the overall quality of the application, encapsulating general requirements and constraints of the system design. Hardware and software components are ranked with respect to digital and radio emission parameters, emphasizing connectivity features. Benchmarking is accomplished by analyzing power consumption and RF characteristics of the synthesis outcomes, evaluating the viability of target solutions. Key parameters consist of input impedance, gain and operating frequency, power consumption, routing, jitter and total harmonic distortion (THD), and electromagnetic interference (EMI) and compatible NFSS emission levels. The stringent requirements of reduced size and cost have a limited impact on the specifications and constructed model. Routing and power consumption represent major bottlenecks in the evaluation of the final application. Power consumption consumption results are highly dependent on circuit topology, determining the base currents flowing into the different devices. The supply current remains quite stable for each test case, as the bias currents are mainly fixed by the reference currents. Worst-case routing congestion is evaluated according to the minimum distance between two parallel wires in the same or adjacent metal layers. The requirement of frequent and wide buses connected to input/output ports is a critical issue with respect to floorplan optimization and layout density. Related work on the use of hands as interaction devices reports a range of methods for gesture recognition. Solutions include camera-based tracking and wearable sensor approaches for motion and pressure measurement. Data gloves equipped with inertial measurement units (IMUs), flex sensors, magnetic trackers, force resistors, or touch sensors have been developed to capture both motion and contact information. Commercially available data gloves exist; however, custom designs are often pursued to achieve specific flexibility and hardware control. The literature lacks standardization and widely reusable designs, leading to replication challenges and diminished study reproducibility [2]. The incorporation of capacitive and inertial sensing modalities permits real-time, edge-based hand gesture recognition with reduced power and memory requirements. Such capabilities enable wireless control of external systems, including drones, with potential extensions to game and industrial robotic applications [14].

10.2. Test Results

The glove underwent functionality and durability testing to evaluate its practical implementation and cost efficiency. A durability assessment involved a cyclical test where the glove was repeatedly bent to simulate typical usage. The results indicated that while the glove is capable of replicating desired motions, the material's resilience to bending requires enhancement to ensure consistent performance over extended usage periods [2].

10.3. User Feedback

Users responded positively to the Montaigne Media Player glove during its preliminary trial, detecting no previous prototype within the system's range and affirming its readiness for continued development [3].

11. Challenges and Limitations

Several challenges and limitations emerged during the design and implementation of a remote-controlled glove utilizing sensor technology.

First, maintaining a low cost with reliable operation proved difficult. Off-the-shelf gesture detection solutions designed for gaming can exceed the affordable range for most users. Balancing quality and affordability is a key issue that requires further work. This concern aligns with a broad consensus that accessible medical-grade devices currently lack economic feasibility.

Second, the glove's design requires optimal positioning and mounting to effectively capture hand movements and transmit corresponding signals. Placement issues may interfere with accurate interpretation of remote-control commands. Proper ergonomics and mounting solutions remain as focal points for improvement.

Third, the user experience suffers limitations in speed and distance of signal transmission. The system currently offers restricted remote operational range and requires extended responsive periods. Enhancing real-time responsiveness and broadening operational coverage remain critical future objectives.

11.1. Technical Challenges

The integration of sensor technology into a remote-controlled glove presents several technical challenges in hardware, software, and power consumption. Although the glove's functionality advances human-machine interaction, the increased number of sensors elevates the robot's cost and weight, and limits the types of tasks feasible due to size and power constraints. The project focuses on the design, development, and implementation of sensor technology for the glove, explicitly excluding hardware assembly and detailed system integration. Subsequently, the developed sensor technology is incorporated into a prototype and utilized to perform remote-controlled actions, facilitating evaluation of system performance and identification of unresolved challenges.

Sensor technology is crucial for constructing a remote-controlled system capable of executing desired movements. In recent years, accurate, stable, and enduring optical sensors have fostered the transition of numerous systems from manual to remote control. In applications such as robotics and gaming, the shape sensor strategy emerges as the most appropriate. The Low Cost Remote Controlled Glove project thus concentrates on the design, development, and implementation of shape sensor technology. The selected technology offers a compact size, rapid output for real-time operation, and correspondingly low power consumption [1].

11.2. Cost Constraints

To contribute to the innovation of sensor-based wearable devices in the context of technological development, a cost-effective and reliable smart glove has been developed leveraging rapid advances in sensor technology [2]. Typically, materials and hardware play a decisive role in cost, making low-cost strategies critical to balance both fabrication and performance of such devices.

The material costs for the proposed wearable system, summarized in Table 1, amounted to under 30 USD. Despite the implementation of a complete hardware design that includes sensing, data logging, transmission, and power supply, the production and fabrication still maintained low overall expenditure. Within the complete system, the inertial measurement unit (IMU) sensor contributed the highest expense at 15 USD, reflecting the presence of multiple sensing elements, including the accelerometer and gyroscope. Nonetheless, more affordable alternatives with fewer integrated sensing elements are available, offering a potential cost reduction avenue at the expense of full system functionality.

From the adopted components, the selected existing three-axis accelerometer and gyroscope model balances cost and accuracy optimally. The embedded communication module further incurs an expense of slightly less than 100 baht, comparable to basic radio frequency modules on the market. For accompanying hardware components and consumables, physicochemical necessities were also considered in the selection process.

11.3. User Experience Issues

Designing and implementing a user-friendly glove on a low budget is demanding, and obtaining immediate feedback is difficult. An online survey conducted to examine potential health risks associated with wearable technology highlighted the need to address usability and hygiene concerns to enhance user satisfaction.

Low-cost gloves satisfying various target user requirements remain challenging for developers and manufacturers. While sophisticated gloves using advanced sensor technology and artificial intelligence exist, they often involve high complexity and cost due to their components. Consequently, inexpensive models tend to focus on limited functionalities, such as vibration signals or basic gesture recognition. Users prefer gloves that offer ease of application without the hassle of intricate setup processes, customization, calibration, or long waits for system startup. Manual adjustment of recognition accuracy is generally unwelcome, contrasting with the desire to increase flexibility without incurring excessive expenses [2].

Additional user experience issues include the absence of dedicated computer software for the glove, limiting its usefulness as a practical interface. Users favor affordable solutions that can be widely deployed in consumer electronics or mobile applications, rather than exclusive high-end features available only in costly units [3].

12. Future Work

Both the Software and Hardware of the low-cost remote-controlled glove using sensor technology system present plenty of room for improvement. On the software side, the setup procedure must be made more automated and robust, and the user interface should be improved for increased ease of use. Additional features can be incorporated as time and resources allow. On the hardware side, integration of the Chrome Cast device and the microcontroller into a single package is desirable, with a preference for a microcontroller that can directly receive IP packets over Wi-Fi, thereby eliminating the need for Chrome Cast entirely. Reducing the time lag in the system should also be a priority.

Although the current prototype sufficiently demonstrates the concept, it is built with a limited budget, and there is ample room to explore ways to lower cost while extending the system to enable furniture control and additional features. Continued development will be guided by these considerations.

12.1. Potential Improvements

The current glove prototype has been successfully implemented, but an evaluation suggests the incorporation of other types of sensors and communication modules could further refine and enhance the design.

The soft robotic glove proposed by Li et al. [3] integrates finger motion tracking and force feedback subsystems. Finger tracking is accomplished using fifteen IMUs mounted on finger rings and connected via a flexible PCB, allowing for easy assembly and efficient SPI communication with the microcontroller; this setup enables real-time hand posture detection. Force feedback is provided by five brushless motors equipped with encoders, housed in a 3D-printed structure that controls nylon wires applying tactile forces to the fingers. Motor control employs field-oriented control (FOC) drivers managed by an ESP32, with wire arrangements that prevent entanglement and allow for easy mounting on a removable support plate. Motor torques corresponding to virtual hand movements generate force feedback that simulates tactile sensations, enhancing realism in virtual reality interactions.

Carfì et al. [2] emphasize the significant role of hand flexibility and range of motion in human interaction and the necessity of capturing both motion and contact information through wearable devices. Common data gloves employ inertial measurement units, flex sensors, magnetic trackers, and force resistors to collect this information. Despite the availability of various solutions, many researchers prefer developing custom data gloves, resulting in limited reproducibility due to a lack of standardization. To address this, the authors propose a modular, open hardware and software architecture tailored for customized IMU-based data gloves, supplemented by an experimental protocol designed to evaluate device performance.

12.2. Scalability Options

Scalability considerations encompass increasing the number of wearable glove components and integrating the system into diverse applications. The architecture permits a single controller board to interface with any number of gloves via a single Universal Serial Bus (USB) connection [2]. Scalability is achievable within current design constraints; however, deploying extra gloves as part of an application necessitates corresponding hardware and software support. Implementing multiple gloves remains feasible, with each connected glove representing a circle of communication. The control system thereby manages several independent circles simultaneously, enabling control over multiple robotic hands or robotic elements. Scaling the system for control of other robotic apparatus requires the development and incorporation of compatible communication protocols, which may also involve modifications to glove hardware and capturing software [15].

13. Applications of the Technology

The low-cost data glove exhibits potential applications across medical therapy, robotic manipulation, and assistive communication. Preliminary insights are drawn from a modular IMU-based glove architecture [2] and a soft robotic glove offering finger-tracking and force feedback for virtual rehabilitation [3].

The glove architecture for stroke rehabilitation couples the data glove with a virtual-reality framework to track and monitor patient hand motion. Finger flexion is ligatured through IMU data, enabling interactive rehabilitation sessions. Incorporating the project’s flex sensors, an alternative motion-tracking approach could reduce patient complexity by measuring flexion angles directly.

Other therapeutic prospects include addressing carpal tunnel syndrome, arthritis, and other conditions requiring fine-motor retraining through similar rehabilitative feedback mechanisms.

Integrating the glove with Dexmo-style haptic-force robots could enhance manual dexterity in precision industries such as watchmaking and jewelry fabrication. The system provides tactile feedback and velocity control during manipulation tasks.

Use in robotic systems leverages the glove’s sensing to remotely control articulated appendages. Pneumatic robots or electric-motor platforms could reproduce human hand gestures for exploration, laboratory analysis, or zonal manipulation without direct human presence, reducing risk in potentially harmful environments.

In assistive communication, the glove system offers solutions for mute or speech-impaired individuals by translating hand signals in conjunction with speech or text-generation hardware. Coupled with facial-recognition technology, it could deliver a comprehensive responsive system.

Military applications might extend to remote handling of explosives, hazardous devices, or support for field medics, staples, dead-reckoning, or defusing hazards, enhancing operational safety and efficacy.

13.1. Medical Applications

Medical applications serve as a prime example of the effectiveness of a low-cost remote-controlled glove. Rehabilitation represents a prominent area of adoption [3]. Rehabilitative activities involving the hand and wrist constitute a significant share of the annual therapeutic workload worldwide. Rehabilitation following stroke, surgical interventions, and injury typically starts with assistance from hospital personnel but subsequently requires extended periods of repetitive activity, often performed at home. A remote-controlled glove can facilitate patient compliance and efficient data collection, ensuring ongoing monitoring and adjustment. A system outfitted with suitable gram-level goggles can discreetly observe patient activity during these exercises.

13.2. Robotics and Automation

The advancement of robotics and automation continues to drive innovative applications in various sectors critical to modern life, including healthcare, manufacturing, and security. Robotics cannot be considered independently today, as automation offers significant support across various industries and daily activities. Humanoid robotics represent a vital focus area, with strategies ranging from elaborate remote control and hybrid automation to fully autonomous operations. Developing a system capable of reading hand signals and transmitting these to a robotic hand to emulate human gestures locally offers valuable opportunities for both research and practical application. Implementing such a system is feasible without incurring substantial costs or long development cycles, as affordable sensor modules— such as accelerometers— and microcontrollers— like the PIC series from Microchip Technology— are readily accessible at reasonable prices. Intelligent sensor technology underpins these capabilities, enhancing computer and manufacturing system performance by facilitating accurate environmental sensing and perception [16].

13.3. Assistive Technologies

Advancements in information processing technology and sensor miniaturization have led to a growing availability of smart systems that integrate various functionalities to enhance user well-being and autonomy. Numerous applications for sensor-equipped, remotely controlled gloves have been developed, allowing users to maintain communication and perform tasks without assistance. Such systems hold particular promise for individuals recovering from strokes, those with paralysis, stroke-like symptoms, or cerebral palsy, as well as for professionals engaged in hazardous operations such as bomb disposal.

Assistive technologies, encompassing a wide range of devices and programs, are designed to improve the functional capabilities of individuals with disabilities or to provide support for those facing challenges in normal living activities. The development of an affordable, sensor-based remote-controlled glove represents a significant step towards creating a practical and cost-effective tool to address these needs. The capability to operate a remote-controlled glove that is affordable, readily available, and user-friendly can substantially reduce reliance on external assistance for patients suffering from paralysis, stroke, cerebral palsy, or similar conditions; it can also facilitate the operation of robots in hazardous environments and prove advantageous to military personnel and smart device users [3] [2].

14. Ethical Considerations

The implementation of low-cost, remote-controlled sensor gloves presents ethical issues beyond pure feasibility. For instance, the wristband's sensors may violate privacy even without intentionally tracking individuals. The glove must therefore incorporate strict safeguards to prevent covert data collection or misuse. Electrical circuits must also be designed to protect users from shocks, and all materials should be non-toxic and skin-friendly to avoid harm.

Wearable devices that communicate wirelessly inside the human body raise obvious health concerns, including possible ionizing radiation, tissue heating, and destructive electrical currents. Additional precautions are necessary, but such devices also offer considerable benefits for support and monitoring of the elderly and disabled, with health implications usually less serious than in consumer-grade mobile phones. Further organic concerns arise from prolonged use of finger sensors, requiring regular breaks and comprehensive safety checks to prevent adverse effects [2].

Under specific ethical conditions, a remote-controlled glove stands out as an attractive option for human-machine interfaces [17]. Assumptions of a medical nature, similar to those outlined above, inevitably affect applications in robotics, particularly concerning the physical interaction between users and robotic grippers. Robotic hands could maneuver guideposts, keys, or handles during inspections on delicate installations, offering a more convenient alternative to direct teleoperation.

14.1. User Privacy

The user of the Remote-Controlled glove is reminded that this device operates in an active sensor mode, constantly transmitting identifiable data to nearby receiving devices. People in range must be made aware that the glove is in use and cognizant of the data being shared.

Contemporary commercial hardware enables energy-efficient methods to activating data transmission and sensing over Bluetooth-aware devices. This approach may be safer in analogy to audio recording devices, which provide audible or visible feedback when in operation.

14.2. Safety Concerns

Safety concerns play a critical role in designing and implementing a low-cost remote-controlled glove with sensor technology, as wearable devices may encounter conditions hazardous to both users and their surroundings. Regarding personal protective equipment (PPE), a wireless “smart glove” was developed to monitor upper limb physiological conditions linked to mechanical stress [11]. A range of sensors—accelerometers, strain gauges, and pressure sensors—detect exposure to damaging vibration, flexion, extension, impacts, and large forces, whereas a dynamic component-tracking system measures time-dependent loading at high sampling rates. Contingent on previously measured safety limits, the glove combines multiple sensor inputs to generate an overall safety rating, communicates with a dedicated RF transceiver, and provides real-time feedback via a small LCD and configurable alarms. The accompanying software supports multiple gloves, displaying the current status clearly and issuing warnings before conditions become dangerous. This methodology prevents repetitive strain injury and establishes an audit trail for workplace compliance.

15. Conclusion

The entire glove has been designed using Autodesk Inventor and printed on an Ender 3 S1 3D printer using PLA filament. Despite PLA's lower durability in hot conditions compared to ABS, internal components remain unaffected. Combined with flex sensors, this glove effectively measures finger bending and movements and reports them to a microcontroller. The final low-cost, lightweight glove can be controlled remotely via a webpage hosted on the microcontroller's access point; physical buttons on this webpage initiate signals controlling the five fingers individually or collectively.

The project extensively explores the Internet of Things (IoT) and the integration of microcontrollers with sensors. Due to the necessity of a reliable real-time sensor, a potentiometer—a precise device for detecting displacement and various mechanical positions—was utilized. The glove can be activated through a web interface hosted on the microcontroller, providing the flexibility to send commands to individual or multiple fingers. Mechanical components were crafted using computer-aided design (CAD) tools and manufactured through 3D printing technology. Considering existing products that often pose either high costs or inadequate connectivity, the aim centered on delivering a cost-effective, accessible solution, rendering the project both innovative and timely.

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