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Original Article

Low-Cost Remote Monitoring System for Hand Rehabilitation Using an Exoskeleton and IoT in Phalangeal and Meningeal Fractures

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Abstract - *In this article, a low-cost, remotely monitored control system is designed for hand rehabilitation using an exoskeleton in cases of phalangeal and meningeal fractures. Hand injuries, including fractures, often require specialized therapy for recovery, and early intervention is critical to improve outcomes, often without a specialist nearby in rural Peru. Therefore, a system is proposed that integrates an exoskeleton device and Internet of Things (IoT) technology to provide remotely monitored control and personalized rehabilitation to patients. The various values obtained from the system are transmitted to a secure cloud platform via the MQTT protocol for access by both patients and specialists, enabling continuous remote assessment, progress monitoring and adjustment of the rehabilitation regimen. Angle, count, speed and strength parameters can be monitored at each therapy session throughout the patient's progress until discharge. Angle, count, speed and force parameters can be monitored at each therapy session throughout the patient's progress until discharge. Real-time visualization of sensor values allows us to quantify the patient's progress. The successful delivery of information is evaluated, and the IoT-based system is cost-effective and offers an innovative approach to address the rehabilitation needs of patients with hand injuries, ultimately leading to faster recovery, reduced healthcare costs and improved quality of life.*

Keywords - *Hand rehabilitation, Healthcare technology, IoT (Internet of Things), MQTT protocol, Low cost, Remote monitoring.*

1. Introduction

In remote areas of Peru, access to specialized medical care remains a challenge for local communities. Phalangeal and meningeal fractures pose particular challenges, as their proper rehabilitation requires expert intervention. Unfortunately, the lack of access to health services has prompted the search for innovative solutions. In this context, a low-cost system has emerged with the aim of revolutionizing hand rehabilitation.

The incorporation of the Internet of Things (IoT) has radically transformed several aspects of everyday life, extending its relevance to the healthcare field. Specifically, in the rehabilitation of phalangeal and meningeal fractures, IoT plays a pivotal role.

By enabling real-time data collection, transmission and analysis remotely, it facilitates continuous monitoring of patient progress. It also opens up exciting possibilities for personalized healthcare and telemedicine, especially in regions where access to healthcare professionals remains limited. The integration of IoT technologies into rehabilitation systems promises more efficient, accurate and accessible care, ultimately improving patient outcomes and quality of life.

The exoskeleton system, designed for hand rehabilitation, is at the heart of this transformative approach. Each finger, independently controlled by servomotors, allows for customized adaptation to each patient's unique needs. Beyond facilitating range-of-motion exercises, this versatile design allows for specialized techniques for meningeal fractures.

However, the impact of this technology goes beyond the clinical setting. By implementing the exoskeleton in remote villages in Peru, where the constant presence of specialists is not feasible, we not only address medical challenges but also contribute to local development. This system becomes a powerful tool that overcomes barriers and fosters social inclusion.

In this project, the convergence of engineering, medicine and social impact is evident. Every component, from the low-cost materials to the carefully selected sensors to measure force and pressure, ensures the system's long-term effectiveness and sustainability. By embracing technology, we overcome barriers and empower communities, improving lives.

This document is divided as follows: The related works are presented in section 2, and the methodology is presented in section 3. Section 4 describes the development of the system proposed; the drone stage subdivides this section, the algorithm developed and the control station. Section 5 presents the test and results obtained. Finally, section 6 presents the conclusions of the research.

2. Related Works

In the context of rehabilitation with exoskeletons and similar technologies, several innovative proposals have emerged, offering significant advances in the field. A notable example is the presentation of an index finger exoskeleton with an innovative design based on a 2-UPS mechanism and Bowden wire [1]. This design not only demonstrated efficacy in performance and comfort testing but also improved accuracy and compatibility in rehabilitation robots.

Likewise, a study that proposes a bio-inspired exotendon routing mechanism for finger flexion and extension simplifying with a single motor and avoiding hyperextension is also highlighted [2]. In the same line, another work presents an electronic system to measure force in a hand exoskeleton robot, allowing accurate measurements of the user's phalanges [3]. These contributions are fundamental for motor rehabilitation, providing results up to 0.9 kg in flexion and 1 kg in extension.

In the field of robotic exoskeletons for finger rehabilitation, a design driven by linear motors and Bowden cables has been proposed [4]. This approach has demonstrated its ability to reach maximum bending angles with a motor force of up to 68. In addition, a wearable finger exoskeleton with a one-degree-of-freedom mechanism based on anthropometric measurements fabricated by 3D printing has been developed [5].

Focusing on post-stroke rehabilitation, an index finger exoskeleton with three motors and a self-aligning mechanism that reduces reaction forces by 65.8% is presented [6]. In parallel, a support glove with a Conducted Cable Mechanism is introduced to reduce weight and facilitate an adaptive grip [7].

In terms of control and optimization, an improved PID controller using a genetic algorithm and backpropagation nerve network is proposed for a rehabilitation handheld exoskeleton robot [8]. This controller has been shown to improve performance under various conditions, reducing the peak time of the output signal and achieving better adaptability to changes in system parameters. Additionally, a finger rehabilitation device with SMA wire and fuzzy neural network PID control has been developed [9]. This prototype has achieved human-like bending angles and effective passive rehabilitation with remarkably reduced response time compared to traditional PID control.

The design and simulation of a finger-assisted exoskeleton for post-stroke rehabilitation is presented in another paper [10]. This system, with multiple degrees of freedom, facilitates bending and stretching exercises, providing a theoretical basis for motion control and exoskeleton fabrication. In addition, an improved design for the rehabilitation handheld exoskeleton robot is proposed, seeking to replace manual intervention by rehabilitators [11]. This design uses a two-way wheel with a sliding guide rod and tandem elastic drive, achieving rotation angles consistent with the human hand and ensuring the stability of the system through the appropriate choice of stiffness and damping.

Another innovative approach is found in the paper proposing an exoskeleton for the index finger based on Bowden line elastic driving [12]. This design allows special force and torque control, addressing limitations of existing exoskeletons and facilitating rehabilitation of people with upper extremity disabilities. In addition, a docile finger exoskeleton with superelastic telescoping drives has been presented, using nickel-titanium rods for flexibility and safety [13]. The design is characterized in detail, demonstrating compliance through finite element analysis and experiments showing flexibility in the flexion/extension motion of the index finger.

In the field of wrist and finger rehabilitation in stroke survivors, an electromechanical exoskeleton was designed [14]. In a pilot study, this device showed significant improvements in clinical measures, showing promise for resource-limited settings. In addition to specific advances in finger exoskeletons, the rehabilitation landscape is expanding with solutions that integrate wearable sensors and remote monitoring technologies. One example is a wearable sensor patch that integrates ECG, PPG, and body temperature for remote health monitoring via IoT [15]. This patch has continuous blood pressure estimation capabilities and wireless transmission to gateways, demonstrating feasibility for connected health applications.

Comparing IoT-assisted technologies and motor training in chronic stroke patients, a study shows that IoT-assisted TIGER technology significantly improves upper extremity functions [16]. This approach highlights its potential in the rehabilitation of stroke patients. In the field of telerehabilitation, a framework with augmented reality has been developed to operate rehabilitation robots remotely [17]. This framework facilitates robot-assisted therapies for people with upper extremity dysfunction through PTC's IIoT platform. The development of an affordable and lightweight exoskeleton system based on the origami rope technique for upper extremity rehabilitation is highlighted [18]. This system presents features such as lightweight mass, user-centered protocols, and biomechanical sensing, control, and actuation systems.

The integration of IoT devices in clinical laboratories, as discussed in [19], not only transforms traditional management but also improves patient care outcomes by enabling real-time health monitoring, reacting quickly to anomalies, and promoting a more connected and responsive healthcare environment. In addition, the urgent restructuring of the rehabilitation system in response to the COVID-19 outbreak, as mentioned in [20], includes the implementation of technologies such as a buck converter to control motors in rehabilitation robots and a real-time remote monitoring system via IoT, which facilitates continuous tracking of patient progress.

Finally, the advancement of technology in Electrocardiogram (ECG) monitoring, discussed in [21], combined with Artificial Intelligence (AI), offers significant opportunities in the diagnosis and treatment of Cardiovascular Disease (CVD), highlighting the importance of collaboration between edge and cloud computing for intelligent ECG monitoring, as well as future challenges in terms of reliability and value of this technology.

3. Methodology

This paper presents a wearable device consisting of a wearable part, a controller (master), sensors, actuators and a smartphone. The master controller is connected to both actuators and sensors. The latter processes and transmits the signal from the sensors for monitoring. Figure 1 shows the diagram of the proposed system.

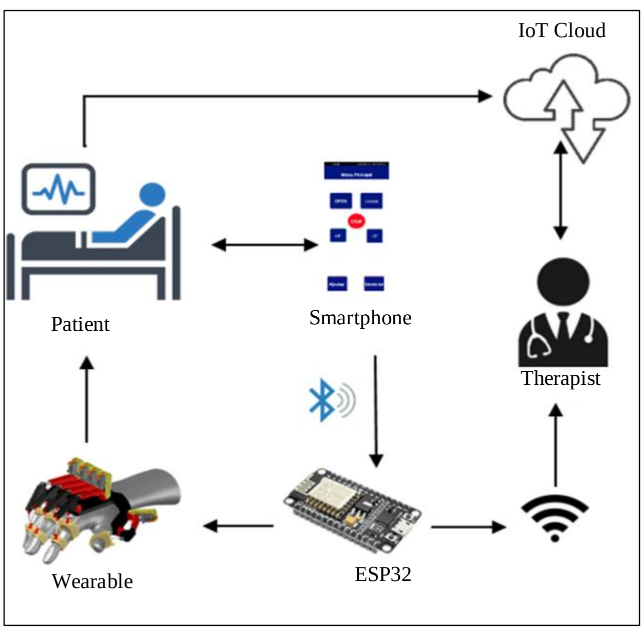

Fig. 1 Methodology

A control method and multiple architectures are used to control handheld devices, process sensor signals and analyze the results of manual exercises. Suggested hardware and control methods are presented in this section: Internet of Things (IoT) based methodology. Three different architectures are also presented:

- Dual Therapeutic Wearable.
- User Therapeutic Wearable.
- Multiuser Therapeutic Wearable.

4. System Development

4.1. Wearable Design

A 3D-printed structure was designed. There is a base for each servomotor, five in total, where connecting rods are placed that are connected to two rings on each finger, except for the thumb, which only has one.

A glove-like structure is one that holds the servomotors and other mechanisms. It is adjusted to the wrist by means of a Velcro grip (Figure 2).

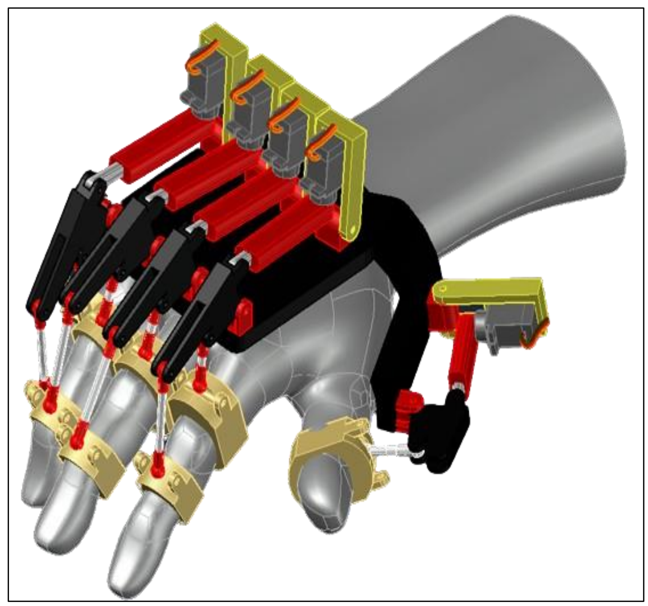

Fig. 2 3D wearable design

4.2. Device

For each finger there is a servomotor to open and close the wearable. This helps users to perform exercises with their hands and practice gripping and moving objects in their rehabilitation process.

The suggested device is made of polypropylene and weighs 450 grams. It will have 3 positions that can be developed with the wearable: an opening movement, a closing movement and an independent movement for each finger where you have to press the FSR sensor that is located on the thumb pad, see Figure 3.

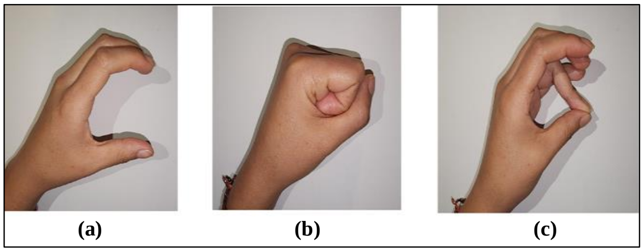

Fig. 3 Movements that are performed in the rehabilitation process with the therapeutic wearable (a) Opening movement, (b) Closing movement, and (c) Independent movement for each finger, where the fingertip of the thumb is pressed to read the FSR sensor.

4.3. Master Controller

A NodeMCU is a master controller that can control servo motors and collect sensor data via a smartphone app or IoT-based control panel. In addition, it can connect wirelessly to the cloud, allowing therapists to store and monitor sensor data, as well as key parameters, indicators and control commands. The ESP32 is used due to its low cost and its Bluetooth and Wi-Fi capabilities, making it one of the best platforms for developing IoT applications. While operating the wearable device, the NodeMCU's Bluetooth wireless communication interface receives instructions from the user. The NodeMCU, flex sensors, FSR sensors and five servo motors make up the electronics of the wearable.

4.3.1. Device's Electronics

A flexible sensor is employed by the wearable to gauge the angle parameter during the opening and closing motion of the device. The voltage at the fixed value resistor's output is the measured parameter, and the voltage divider is powered by an ESP32 at 3.3 V. By measuring the voltage, knowing the supply voltage, and knowing the value of the resistor terminating the voltage divider, one can calculate the resistance of the sensor at the points under study. To ascertain the patient's state of recovery, ranges are set based on the resistance value provided by the flexible sensor (See Figure 4).

The flexible sensor is made with Velostat because it produces the same results as a commercial sensor [19]. This material exhibits a wide range of resistivity under stress, making it ideal for gathering various measurements that are crucial for determining the flexion of the hand's finger joints.

One servo motor is used on each finger; due to its size, SG90 micro servos were used. It has a torque of 1.6 kg/cm and 180° position control. The Switching Mode Power Supply (SMPS) and rechargeable batteries are the two main sources that provide power. The batteries are useful to make the device portable, for example, when traveling, and the SMPS are useful when the user is anywhere with electrical facilities, such as in a hospital or at home.

The circular FSR sensor provides resistance corresponding to the voltage. The sensor is to be connected to the analog input of the ESP32 for voltage measurement. Placed on the thumb during therapy exercises, it allows patients to measure the pressure force exerted by each finger of the hand. Since it operates as an analog sensor, the values range from 0 to 1023. These values can be used to establish pressure ranges, thereby determining the force exerted by each finger and defining recovery stages. For instance, 0-9 indicates no pressure, 10-199 suggests low recovery, 200-499 implies medium recovery, 500-799 denotes high recovery, and 800-1023 signifies successful recovery. This methodology facilitates the acquisition of strength parameters.

The count, recording the number of opening and closing cycles; the angle, representing the amplitude of opening and closing movements ranging from 0° to 90°; the speed, adjustable to control the rate of opening and closing of the wearable; and the force, indicating the pressure capacity measured on each finger, constitute the four primary parameters to control. Grip and pressure indicators derived from sensor data are captured during the device's opening and closing actions.

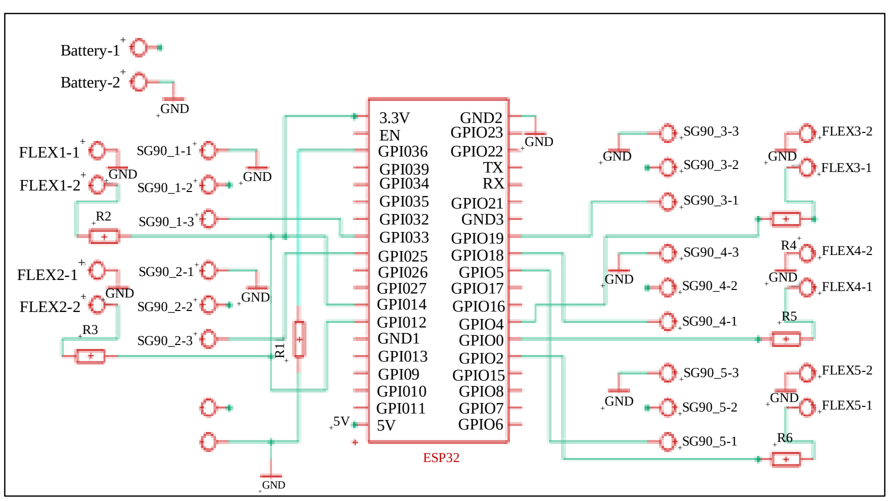

Fig. 4 Therapeutic wearable schematic

4.4. Internet of Things (IoT) Based Control Method

The four parameters-count, angle, speed, and force are monitored by the smartphone application. The therapy begins with low angles of opening and closing. Similar to this, as therapy advances, so do the opening and closing times as well as their speed.

It displays the Internet of Things interface that, when the patient is undergoing therapy, can use the cloud to send signals to the NodeMCU to initiate the opening and closing movements. For both the patient and the therapist, it is an extremely straightforward and user-friendly interface (See Figure 5).

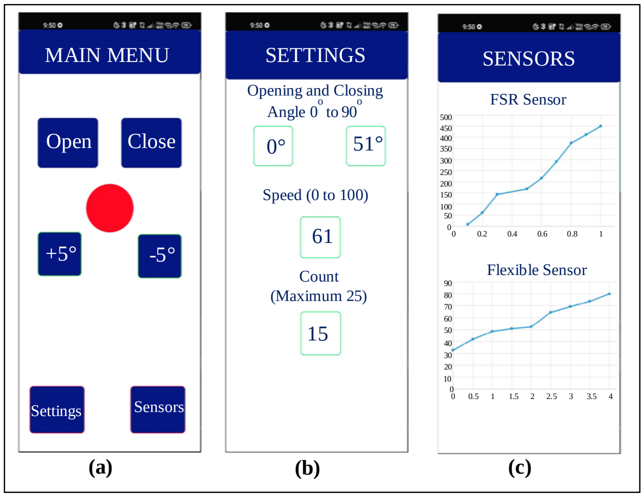

Fig. 5 Developed interface a) Home, b) Settings, and c) Sensors.

It has two switches for opening/closing movements and a STOP button to stop all movements. Angle degrees can be added or decreased in 5° intervals. Sensor data is displayed in a graph and stored in the cloud for future reference or reporting of therapy progress.

4.5. Architectures

4.5.1. Dual Therapeutic Wearable

This architecture is intended for programs involving remote therapy, in which the patient is treated remotely from home or another location, and the therapist works from a hospital or rehabilitation facility. Though the wearable is under the patient's and therapist's control, the therapist can keep an eye on things and take command if the patient has any questions. Cloud storage is used to store sensor and parameter data for later use and analysis. This makes it possible to create a customized recovery plan for every patient (See Figure 6).

It is important to consider that there are delays associated with both the sending of sensor values and the wearable's remote handling, or latency, which is measured in seconds. This building's architecture is intended for patients who will be released and need to continue with their therapy programs at home.

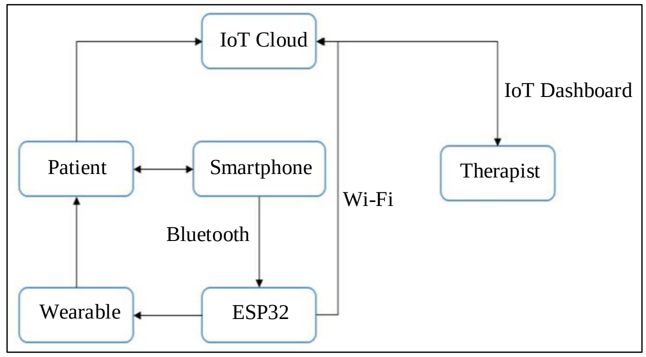

Fig. 6 Dual therapeutic wearable architecture diagram

4.5.2. Therapeutic Wearable for the User

With this architecture, the therapist can monitor the patient's progress by visualizing the data from the sensors and parameters on the cloud. In contrast, the patient maintains complete control over the wearable and can customize their therapy sessions (See Figure 7).

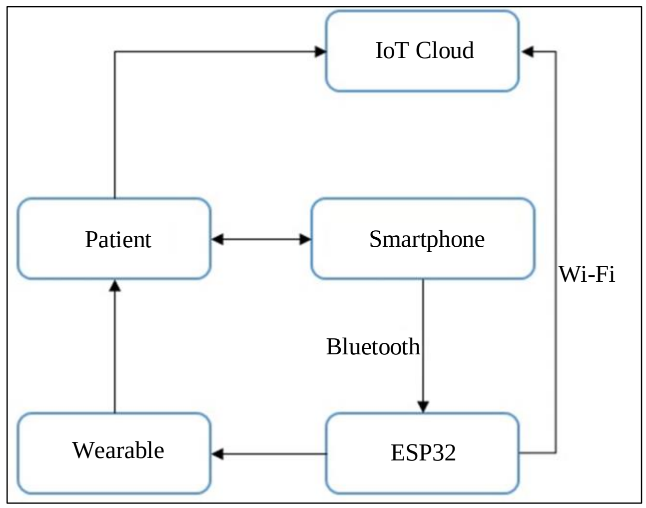

Fig. 7 Wearable therapeutic wearable architecture diagram for the user

It is acknowledged that this architecture is designed for advanced patients who are familiar with and adept at using the wearable device's management system and smartphone application interface.

4.5.3. Multiuser Therapeutic Wearable

With this architecture, a therapist can oversee multiple patients concurrently, analyze and track real-time sensor and parameter values, and store all of this data on the cloud. This architecture has the benefit of allowing the patient and therapist to be in different locations during the therapy session and still be able to work through the exercises with ease (See Figure 8).

The wearable data is sent to the cloud using the MQTT (Message Queuing Telemetry Transport) protocol, and this protocol is suitable for the proposed architectures as it uses the many-to-many protocol for data exchange between clients and servers; it works over the Transmission Control Protocol TCP/IP Internet Protocol.

The target population for this wearable is people with limited resources who typically live in remote areas of the city where internet speed is slow. As a result, this protocol requires bandwidth for communication, which helps to control the wearable even when the internet speed is low.

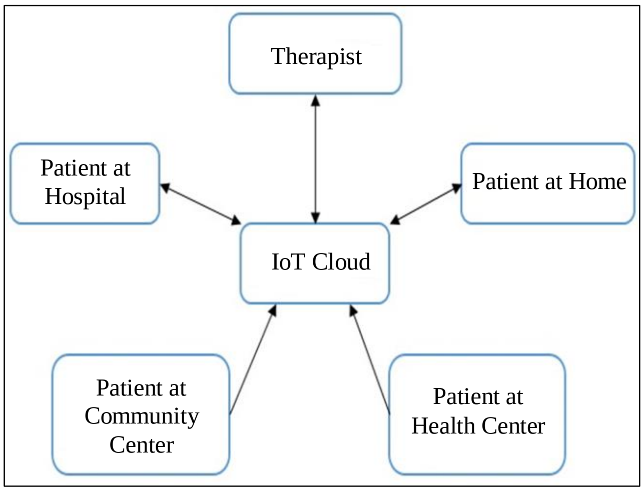

Fig. 8 Multiuser wearable therapeutic architecture diagram

5. Test and Results

In this section, the proposed IoT architectures are evaluated based on important parameters such as latency, data loss, and the type of network. These criteria are crucial for assessing the efficiency of the IoT system.

In the following tables, the latencies and data loss observed during testing with 15 participants across different networks are presented. The following legend will aid in understanding the tables:

- S1 (Reception of data through the cloud by the therapist)
- S2 (Control at the interface by the therapist)
- S3 (Control at the interface by the patient)
- S4 (Reception of data through the cloud by the patient via mobile application)
- M1 (Dual Therapeutic Wearable Architecture)
- M2 (Therapeutic Wearable Architecture for the user)
- M3 (Multiuser Therapeutic Wearable Architecture).

Table 1 presents the latencies of the four operations (S1, S2, S3, and S4) within different proposed architectures (M1, M2, and M3). It is evident that latency is higher in a 3G network (both for receiving and sending data to the cloud) compared to a 4G network. For instance, in the Wearable Therapeutic Multiuser Architecture, the patient requires 2.64 seconds to receive data from the cloud using a 3G network. In contrast, the same data takes 2.19 seconds to be received from the cloud using a 4G network.

Table 1. Latencies on different architectures

	Latency(s)							
	3G				4G			
	S1	S2	S3	S4	S1	S2	S3	S4
M1	2.41	2.53	0.92	2.42	2	2.16	0.53	2.05
M2	-	-	0.95	1.51	-	-	0.63	1.13
M3	2.63	2.62	0.81	2.64	2	2.21	0.58	2.19

Tables 2, 3, and 4 depict the data loss for various architectures detailed in this article. Here, we observe a maximum data loss of 1000 samples per second and a minimum of 700 samples per second. It is noteworthy that significantly higher losses occur when utilizing a 3G network compared to a 4G network.

Table 2. Data loss in therapeutic wearable architecture dual

Therapeutic Wearable Architecture Dual (M1)				
Sampling Frequency (Samples/S)	Data Loss (%)			
	3G		4G	
	S1	S2	S1	S2
700	1.5	2.3	0.1	1.8
800	1.9	3.2	0.5	2.4
900	2.1	4.8	2.2	3.5
1000	8.3	12.2	4.9	9.9

Table 3. Data loss in therapeutic wearable architecture for the user

Therapeutic Wearable Architecture for the User (M2)				
Sampling Frequency (Samples/S)	Data Loss (%)			
	3G		4G	
	S1	S2	S1	S2
700	-	2.1	-	1.4
800	-	3.2	-	2.5
900	-	4.8	-	3.1
1000	-	12.3	-	9.3

Table 4. Data loss in therapeutic wearable architecture multiuser

Therapeutic Wearable Architecture Multiuser (M3)				
Sampling Frequency (Samples/S)	Data Loss (%)			
	3G		4G	
	S1	S2	S1	S2
700	1.5	2.4	0	2.4
800	2.1	3.8	0.5	3.5
900	2.1	5.1	1.9	3.8
1000	8.1	12.7	5.4	10.2

Table 5. Latency variation in multiuser therapeutic wearable architecture as a function of the number of users

	Latency(s)							
	3G				4G			
	S1	S2	S3	S4	S1	S2	S3	S4
2	2.61	2.67	-	2.7	2.01	2.14	-	1.98
3	3.12	3.11	-	3.09	2.59	2.33	-	2.51
4	2.85	2.93	-	2.74	2.14	2.21	-	2.19
5	2.81	3	-	2.99	2.57	2.28	-	2.48

Table 6. The time it takes for the wearable to reach the desired angles at different speeds

Angle	V1 (s)	V2(s)	V3(s)	V4(s)	V5(s)
15°	0.75	1.1	1.28	1.49	1.79
30°	1.02	1.32	1.78	2.46	2.99
45°	1.25	1.68	2.28	3.1	4.08
60°	1.49	2.01	2.84	4.09	5.17
80°	1.79	2.38	3.71	5.24	6.78

Regarding the Multiuser Therapeutic Wearable architecture, tests were conducted across various scenarios, varying the number of connected users to measure latency. The objective was to verify whether the presence of multiple users connected would lead to increased latency. According to Table 5, it is confirmed that as the number of users increases, latency increases relatively. However, it is a minimal increase, validating that the system works for multiple users connected simultaneously.

The time taken to perform opening and closing movements is also evaluated based on the angle and speed defined in the user interface. Angles of displacement of 15, 30, 45, 60, and 80 degrees are selected, with a repetition count of 25. Five speeds (V1, V2, V3, V4, and V5) are tested. The results are shown in Table 6, where it is evident that at higher speeds and angles, the wearable takes more time to perform the movements.

6. Conclusion

This article focuses on the development of a wearable device based on IoT technology for hand rehabilitation. The integrated sensors are manufactured in laboratory environments to achieve a low-cost device, as the target audience lacks high economic resources. Several architectures (dual, for a single user, and multiuser) with an IoT-based control method are proposed, allowing remote control of the wearable device, as well as recording, storing, and reading sensor data that enables both the therapist and the user to track their rehabilitation progress.

A user-friendly and didactic interface is proposed for easy use and understanding by both the therapist and the patient. This significantly reduces the cost of having a permanent and in-person therapist, allowing the patient to undergo their rehabilitation process individually. Acceptable latencies and data loss rates are achieved in both 3G and 4G networks, validating its use in remote areas away from the city. As part of future work, the aim is to implement additional control methods such as voice recognition and the integration of Artificial Intelligence to personalize and automatically update the rehabilitation program.

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