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Machine Learning-Assisted Wearable Thermo-Haptic Device for Creating Tactile Sensation

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Abstract
The tactile modality is an important source of human experience and emotional expression, either on its own or by intensifying and complementing other senses, influencing our interactions with objects, people, animals and other beings. Following this, developed haptic devices transmit information to the user using tactile stimuli to increase or change sensory input. Haptics are an important factor that makes virtual worlds and remote interpersonal interaction tangible. Haptic feedback consists of more components that make an experience physically perceptible and realistic. Haptic feedbacks are widely used in mobile and wearable devices to convey various types of notifications to users. In this study, it was aimed to develop a new generation of wearable gloves against the hypoesthesia problem by combining artificial intelligence and thermohaptic, which are popular in many fields.

1. Introduction

The survival of all organisms (plants, animals, fungi, etc.) depends on their ability to sense touch, perceive and respond to various external stimuli [1]. Touch is the sensation experienced when the skin interacts mechanically or thermally with an object [2]. Chemicals, mechanical force, temperature and pH are clues that provide information about safe and dangerous environments through pain sensations [1]. A basic biological function of pain sensations; It is to direct the organism's attention to injury and damage and to protect it from further injuries by triggering or blocking movement [3]. For many years, human skin has been considered as information-transmitting receptors. Skin sensations such as pressure values and stretching transmit tactile messages that are carried to the brain via afferent nerves. [4].

Tactile information is collected on the skin by numerous receptors, which are special end organs of the peripheral nervous system. Numerous receptors help convert thermal, noxious, itching or chemical stimuli into neural information. [5]. Tactile sensation and tactile perception change proportionally with age. Starting from the age of 20, people gradually lose their sensitivity to external stimuli such as touch, pressure and vibration. These changes that occur with age depend on both skin characteristics and the central nervous system. The structure and number of sensory receptors in the skin, including the most sensitive receptors, change as the person ages. Changes in brain map areas can affect tactile perception in individuals with conditions such as stroke and diabetes. Approximately 3/4 of stroke patients occur in people over the age of 65. However, in addition to age, stroke may cause abnormal somatosensory function in 50-80% of cases. [6]. Stroke is the 3rd cause of disability and the 2nd cause of death worldwide. The most common disability that occurs after a stroke is hemiparesis of the upper extremity. This situation affects the life activity and peace of mind of 50%-70% of paralyzed individuals. While approximately 80% of sick individuals experience acute hemiparesis, 40% may experience this condition chronically. [7]. Individuals who experience this condition chronically may have lower skin perception, which impairs their ability to touch, perceive and press. It can reduce sensitivity to emotions. [6]. Among the most common

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effects of stroke is the impairment of hand functions. People who have a stroke often experience permanent movement disorders. [8]. Severe hand or upper extremity weakness occurs in approximately 87% of stroke patients [7]. Treatment methods for sensory deficits are inadequate, and these have traditionally been addressed with compensatory strategies in physical therapy [9]. As the average age of the world population increases, it is predicted that these problems will increase, considering the tendency of the elderly population to sensory disorders. Due to the lack of treatment that fully restores sensory functions, approaches that aim to increase the standard of living or replace deficiencies can serve as effective alternatives. [4].

Previous work on haptic devices; showed that user preference for touch communication is haptic devices rather than vibration [10]. The term haptic; It allows us to manipulate objects and textures around us, temperature, pain, etc. It is defined as allowing us to detect sensations and perceive emotions [11]. Haptic feedback consists of more components that make a behavior physically detectable and realistic [12]. Tactile feedback is widespread in wearable technologies and mobile applications by providing various types of notifications to individuals [13]. These devices generally lack thermal feedback, although they are not separated from the sense of touch [10]. Temperature is an effective communication tool in our lives because human skin perceives a wide temperature range with high resolution [14]. Lack of temperature sensitivity or lack of sensation leads to avoidance of useful tactile information such as avoidance of extreme temperature and psychological comfort. Additionally, the lack of temperature feedback causes tissue damage through exposure to high temperatures [15]. Therefore, “thermo-haptic” devices are important for people with hypoesthesia.

Thermo-haptic technology is a method that allows people to sense temperature changes [16]. This technology is used especially in wearable devices such as gloves, allowing the user to sense the temperature of objects around them. Temperature perception plays an important role in daily life; for example, knowing whether something is too hot or feeling the surface temperature of an object. By providing this type of sensory information, thermo-haptic technology helps people experience their environment in a richer way.

Today, many wearable device studies are being carried out to overcome the difficulties caused by sensory loss and to enable patients with tissue loss to perceive their environment with their hands [14]. Wearable devices are in physical contact with human skin and convey different sensations to users through sensory feedback. Sensory feedback generally includes the senses of hearing, sight, taste, smell and touch. [12]. Chen suggested that temperature is one of the important factors when defining the material in thermal haptic feedback research [17]. Ho et al. conducted a study to verify the role of temperature information in material identification and positioning. [18]. Peiris et al. [19] by integrating the Peltier device into the 'Head Mounted Display (HMD)' device, it provided temperature feedback directly to the user's face [20]. To simulate the sensation of penetrating the body, Peng and others used thermal feedback. Existing studies have enabled people to truly feel tactile information in virtual environments by stimulating various sensory receptors on the skin and to reproduce this interaction to the user [21]. Yunus et al. developed a new wearable edge device to automatically calculate clinically important gait features in real time, as mobility features collected in daily life better reflect a person's walking capacity and complement clinical gait analysis [22]. These thermal technology-based studies demonstrate augmented reality (AR) / virtual reality (VR), but there are deficiencies in temperature transfer between limbs. In order to fill the gap in the literature, it is aimed that during the interaction, the user sends thermal information about an object and the temperature is felt by the thermistor sensor on the glove, and the temperature is detected from the other hand, where there is no hypoesthesia, and the hand reacts.

It is difficult to understand how patients with hypoesthesia detect extreme temperatures and pain, and therefore it is important to investigate these areas in future studies to improve the quality of life of these patients. The importance of tactile technologies is increasing with the acceleration of the technological and industrial revolution that has emerged with the spread of new generation information and communication technologies such as artificial intelligence, IoT (internet of things) and blockchain technology. [23]. The Internet of Things (IoT), which entered our lives with Industry 4.0, is a collection of devices that can detect environmental situations with various sensors and hardware that communicate between electronic devices and produce data [24]. The effective use of artificial intelligence (AI) and machine learning (ML) techniques in this study is innovative and importantMachine learning, especially deep learning and artificial neural networks, have been used to perform a variety of cognitive tasks. These technologies are used to increase the ability of

thermo-haptic devices to detect temperature and create tactile sensations.
Machine learning is a branch of artificial intelligence developed so that computers can learn from experience and make predictions based on given data. This technology can produce accurate results for new situations by learning from examples and using algorithms. Machine learning is used in various fields today, and in this study it was used to improve the temperature sensing capabilities of thermo-haptic devices. In summary, machine learning is a technology that allows computers to learn and develop like humans.

2. Haptic Feedback

The human touch system, with the skin at its center, has an advanced structure. Considering the location of the sensory input, the sense of touch is grouped as cutaneous and kinesthetic sense. [25]. Tactile sense is our ability to feel objects through our skin. Thanks to this sense, we can perceive the texture, hardness, temperature and other physical properties of objects around us. Tactile sense plays an important role in daily life; for example, when holding a glass or writing. Thermo-haptic devices mimic tactile sensation, allowing users to feel objects in virtual environments or in the real world. Skin sensation focused on in this study; It has different sensory receptors such as mechanoreceptors, thermoreceptors and nociceptors. The skin is full of different types of mechanoreceptors that can convert tactile stimuli into electrical nerve impulses that are transmitted to the brain. These stimuli are defined as information that is encoded as action potentials and then interpreted in the brain. After the stimulus comes into contact with the skin, it is encoded by the relevant mechanoreceptors. It is then transmitted to the synapses through nerve fibers, and the synapses transmit it to the brain for processing and interpretation. As a result of the rich features of the touch system, people use it as a useful and successful communication tool in transferring auditory, visual and thermal information.

3. Materyal and Method

Artificial Intelligence (AI) aims to design machines that can perform many cognitive tasks at a level similar to or higher than human intelligence. It is a very rapidly developing branch of computing [27] , [28] . Machine learning (ML) is a subfield of artificial intelligence that involves computer algorithms [28] It is aimed at the development of artificial neural networks, designed to train and teach a machine to solve a problem or pre-perform complex tasks without special programming and is shown in Fig.1 (Deep Learning, Machine Learning and Artificial intelligence) [29].

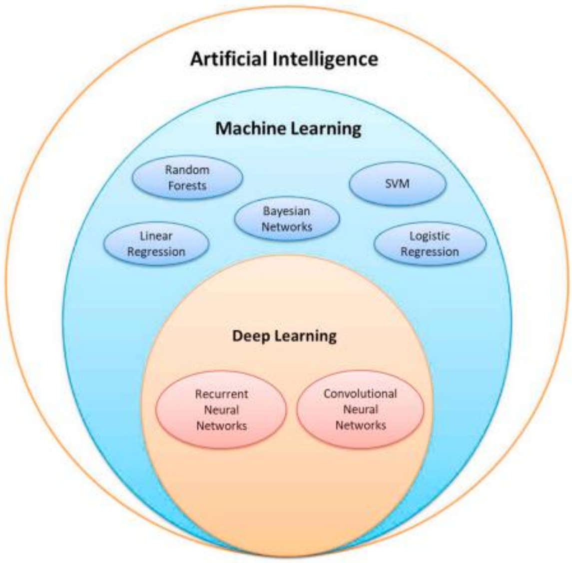


Figure 1. Artificial intelligence, machine learning and deep learning

Artificial intelligence, which has revolutionized many fields, continues its development in medical technology without slowing down. It can cope with different medical problems by developing applications in many fields that often contain large amounts of data [30]. AI applications are developing and shed light on the development of medicine by guiding the course, prevention and personalized treatment of patients in a shorter time [31]. Glove and Edge Machine Learning with Piezoelectric Sensors Fazio et al., a wearable glove enables gesture and object recognition using piezoelectric sensors. This glove classifies detected signals using machine learning algorithms and provides different tactile feedback. This provides an example of how machine learning can be used in wearable haptic devices [32]. Use of Machine Learning in Smart Gloves Ravenscroft et al. , a wearable patch records and decodes non-sound signals using machine learning algorithms. This patch can predict spoken words by detecting throat movements and transmits these predictions to the user with haptic feedback. This work is a concrete example of how machine learning can be integrated in haptic devices [33]. Machine Learning for Haptic Feedback Wang et al. examined new sensing, actuation and control techniques for haptic interaction and teleoperation. This study shows how machine learning can be used in the design of haptic devices. She studied new sensing, actuation and control techniques in haptic interaction and teleoperation and demonstrated the potential of this field. [34]. However, our current work focuses on improving real-world interactions of individuals with tactile sensory loss by applying these technologies to thermo-haptic feedback devices.

In addition, while existing research in the literature generally focuses on a specific type of sensory loss, this study provides a much broader range of applications using the combination of thermo-haptic sensing and machine learning. In conclusion, the current study provides a new and effective solution for individuals with tactile sensory loss by filling gaps in the literature and extending the findings of previous research. This should be considered a novelty in our field and open new avenues for future research.

3.1. System Design

The temperature sensing system will detect the object temperature and ensure that the measured temperature is felt by the user. The temperature sensing system used in the study has a structure that detects object temperatures and makes them felt to the user. The developed system consists of hardware and software components. Hardware components include ESP32 and ESP8266 microcontroller modules, DS18B20 temperature sensors, Converter, Relay and Peltier components. Hardware components are shown in Figure.2 and Figure.3 (system hardware components).

To implement this idea, we need to use microcontrollers that can support wireless interfaces. Controllers with the required features are ESP32 and ESP8266. In this proposed system, while the materials and methods were being developed, preferences in the element base were given to microcontrollers with internal transmission modules (Wi-Fi, Bluetooth) [35]. Based on this, the components used are; ESP32 and ESP8266 as primary controllers, 2 DS18B20 sensors for object temperature measurement, Peltier to sense the temperature, Converter to provide the high current and low voltage required by the Peltier, Relay to keep the temperature at the desired level, DC12V 3A Power Supply for the operation of the system. The system hardware content consists of two parts: "Data Collection" and "Data Processing".

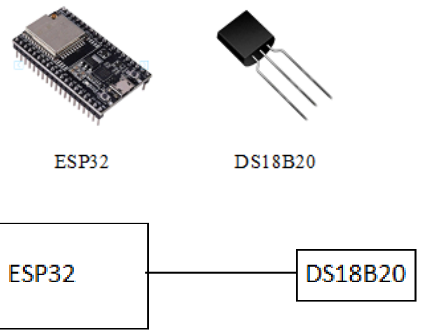


Figure 2. Hardware components and circuit diagram used for the data acquisition and preprocessing system.

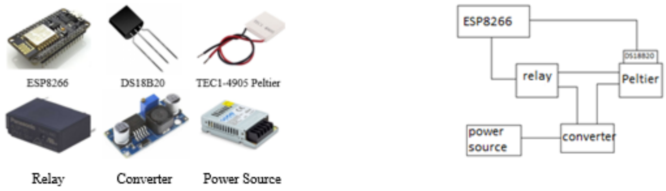


Figure 3. Hardware components and circuit diagram used for the data processing system.

3.1.1 Data Collection and Preprocessing

The data acquisition section is the section where the object temperature is taken. The data acquisition circuit is designed using ESP32 module and DS18B20 temperature sensor. System hardware components and circuit diagram are shown in Figure 2.

ESP32 Microcontroller module

In a short time since its launch, the ESP32 microcontroller has been deployed especially in embedded systems and has been fully integrated into different IoT tasks [36]. Being a price-performance product, its circuit structure offers unique use for creating applications in addition to the possibility of connecting peripheral units, IoT modules and other sensors used. ESP32 module is well implemented as a web server, using Wi-Fi and Bluetooth communication to exchange messages in the environment [37].

DS18B20 Temperature Sensor

DS18B20 is a digital body temperature sensor that gives accurate temperature values and does not require ADC [38]. This sensor helps measure temperature between -55°C and +125°C (-67°F and +257°F). Data received from a single cable ranges from 9-bit to 12-bit. DS18B20 can be controlled by a single pin of the microcontroller after connecting this sensor to GND. Each DS18B20 sensor is equipped with a 64-bit serial code that helps control multiple sensors through a single pin of the microcontroller. In simple terms, it assigns different addresses to all connected sensors and allows us to get the value of those sensors by calling the address. DS18B20 sensor has 3 pins in total, these are;

Pin 1: VCC (+5 V is the pin that should be supplied.)

Pin 2: Data Pin (This is the pin where we will get temperature readings.)

Pin 3: GND (This is the pin where the ground connection is made.) [39]

The most important feature of this sensor and the reason why it is preferred is that it allows reading data, that is, body temperature, directly from the skin and sending it to the microcontroller without the need for a different power source [40].

3.1.2 Data Processing

The data processing section is the section where object temperature is felt. The data processing circuit is designed using ESP8266 module, DS18B20 temperature sensor, Converter, Relay, Peltier and Power Supply. Data processing system hardware components and circuit diagram are shown in Figure 3.

ESP8266 Microcontroller Module

The ESP8266 module provides a unique and standalone Wi-Fi networking solution. It can be used to keep applications or transfer Wi-Fi network tasks from another application module. When the application is launched, it starts directly from the external flash and has the feature of transferring it to the built-in cache to increase the system working level with these applications. It is one of the most available and integrated Wi-Fi chips in this field [41]. This microcontroller produced by Espressif has become the preferred component due to its very low price, very few external components on the module and its Wi-Fi connectivity feature. ESP8266 plays a very important role in reducing the hardware of the system [42].

Peltier

The Peltier component used in the study is defined as a device that is used as a heat source on both sides and has the appearance of a thin plate. In the component, the thermocouple principle applies direct current voltage to two different devices. Depending on the direction of the current, heat is absorbed on one side while heat is produced on the other side, and this is called the Peltier effect. Additionally, heat is absorbed at low temperatures and released at high temperatures. Thus, Peltier acts as a heat pump, sending heat from the low-temperature region to the high-temperature region. Temperature changes the direction and current of the heat pump. Therefore, the Peltier component acts as a semiconductor element that changes the amount of heat pumped to provide free cooling, heating and temperature control. Among the reasons why it is preferred are its small size, lightness, possibility of manufacturing according to desired dimensions, lifespan and reliability. It reacts instantly to temperature changes. In addition, it is preferred because it does not contain any parts that could cause mechanical fatigue or damage [44]. In the study, TEC1 4905 peltier model was used to physically convert the temperature signal received from Data Collection into temperature. The temperature value felt in the transmitter was adjusted with the temperature sensor (DS18B20) mounted on the hot surface. It is a thermoelectric element that can quickly heat or cool according to temperature change. In this study, it was used to observe how quickly Peltier reacts to temperature changes of hot or cold objects touched by the glove.

Relay

The relay, which acts as a source, consists of a console inlet that is fixed to one end and operated laterally, and 3 fixed side electrodes: drain, gate and body. It serves as a contact to pass drainage current. Used to run gates. The body is used for a constant DC bias voltage to reduce the effective tripping threshold voltage of the relay [45]. The relay coil with current passing through it creates a magnetic field and attracts the contacts. Thus, the relay contacts change position. In the study, a relay with contact current of 5A, coil voltage of 5VDc and coil current of 40mA was used. The relay aims to keep the temperature at the desired level. The converter energy was controlled by a relay and used to energize and heat the peltier when the temperature increase signal from the data collector reached the data processing. For cooling, the relay energy was cut off, leaving the peltier without energy and a natural cooling process was achieved.

Converter

In this study, a DC-DC converter based on the use of LM2596 adjustable voltage step-down power module was preferred to control the output voltage. This module is a converter voltage regulator that can drive a 3A load with high efficiency, excellent linearity and load regulation [46]. The converter was used to provide the high current and low voltage required by Peltier.

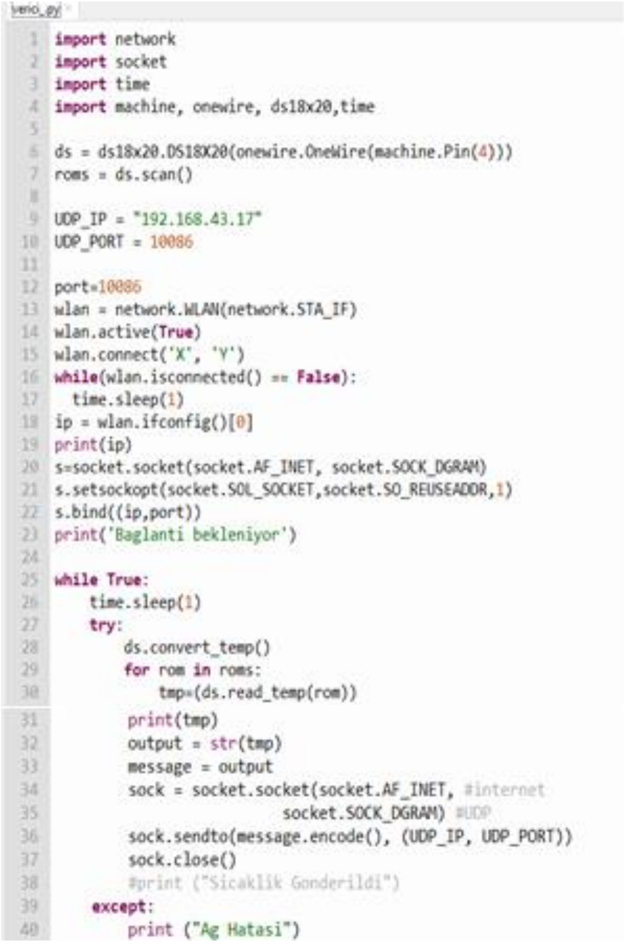
Power Source

A 12 Volt 3 Ampere power supply was preferred to provide the energy needed to operate the device. The purpose of choosing this power supply is to convert high voltage to low voltage and alternating current to direct current. It protects the Data Processing system from voltage or current fluctuations.

3.1.3 Software Components

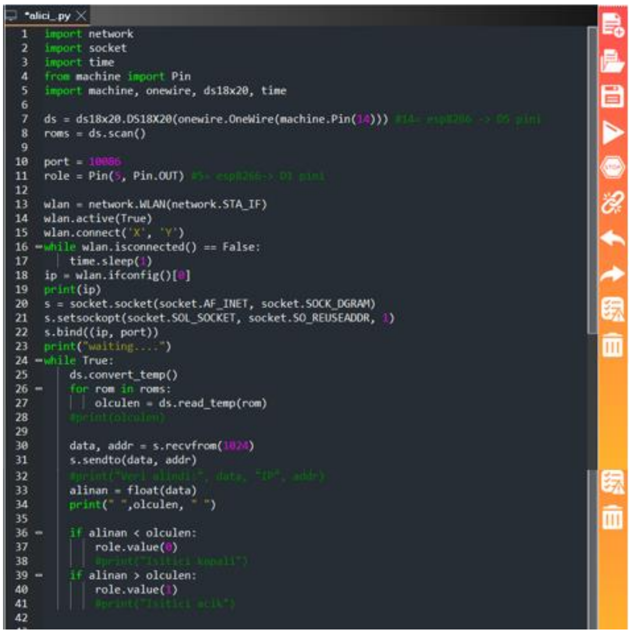
Computer programming has become an essential tool for academic and professional development. Traditional programming languages like C/C++ are much slower in terms of writing code and detecting errors. Computer programming that detects and corrects errors in software codes can cost approximately 20/25% of the software project [47]. Because of this , it is very important to choose an appropriate programming considering the cost of the project. In the software development process, the speed of writing and debugging code is also important. For this purpose, MikroPython was used because this language offers faster results than traditional programming languages. ESP32 and ESP8266 microcontrollers were programmed with MicroPython and Thonny IDE and uPyCraft Integrated Development Environments (IDE) were used. In terms of code writing and error detection speed, Micropython works 5-10 times faster than traditional programming languages [48].

MikroPython is defined as an open source, simpler and more effective implementation of the Python 3 programming language. It is an interpreter optimized to run on small embedded development cards. It has clean and simple syntax to take control of the hardware with 93% code coverage. REPL stands for read evaluation print cycle. It is a MikroPython interactive command prompt that allows you to connect it to the board just to experiment with the hardware without any editing or installation process. The codes work meaningfully and robustly. This implements logical concepts with fewer lines of code [49]. In this study, uPyCraft Integrated Development Environments (IDE) and Thonny IDE were preferred to program ESP32 and ESP8266 boards with MikroPython. The software component consists of 2 parts: Data Collection Software Part and Data Processing Software Part. System Codes are shown in Figure 4. and Figure 5.



```
veri_py
import network
import socket
import time
import machine, onewire, ds18x20,time

ds = ds18x20.DS18X20(onewire.OneWire(machine.Pin(4)))
roms = ds.scan()

UDP_IP = "192.168.43.17"
UDP_PORT = 10086

port=10086
wlan = network.WLAN(network.STA_IF)
wlan.active(True)
wlan.connect('X', 'Y')
while(wlan.isconnected() == False):
  time.sleep(1)
ip = wlan.ifconfig()[0]
print(ip)
s=socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
s.setsockopt(socket.SOL_SOCKET,socket.SO_REUSEADDR,1)
s.bind((ip,port))
print('Baglanti bekleniyor')

while True:
    time.sleep(1)
    try:
        ds.convert_temp()
        for rom in roms:
            tmp=(ds.read_temp(rom))
         print(tmp)
         output = str(tmp)
         message = output
         sock = socket.socket(socket.AF_INET, #internet
                              socket.SOCK_DGRAM) #UDP
         sock.sendto(message.encode(), (UDP_IP, UDP_PORT))
         sock.close()
         #print ("Sicaklik Gonderildi")
     except:
         print ("Ag Hatasi")
```

Figure 4. Data acquisition software code



```python
import network
import socket
import time
from machine import Pin
import machine, onewire, ds18x20, time

ds = ds18x20.DS18X20(onewire.OneWire(machine.Pin(14))) #14= esp8266 -> D5 pini
roms = ds.scan()

port = 10086
role = Pin(5, Pin.OUT) #5= esp8266-> D1 pini

wlan = network.WLAN(network.STA_IF)
wlan.active(True)
wlan.connect('X', 'Y')
while wlan.isconnected() == False:
    time.sleep(1)
ip = wlan.ifconfig()[0]
print(ip)
s = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
s.setsockopt(socket.SOL_SOCKET, socket.SO_REUSEADDR, 1)
s.bind((ip, port))
print("waiting....")
while True:
    ds.convert_temp()
    for rom in roms:
        olculen = ds.read_temp(rom)
    #print(olculen)

    data, addr = s.recvfrom(1024)
    s.sendto(data, addr)
    #print("Veri alindi:", data, "IP", addr)
    alinan = float(data)
    print(" ",olculen, " ")

    if alinan < olculen:
        role.value(0)
        #print("Isitici kapali")
    if alinan > olculen:
        role.value(1)
        #print("Isitici acik")
```

Figure 5. Data processing software code

The data collection and processing section of the system are the main parts where temperature readings are taken and temperature values are processed. These sections are supported by software codes that send data to predefined IP addresses and process the received data.

Data Acquisition Software Section

Thonny IDE coding tool makes it easy to create, debug and test code. It offers a number of useful features, including code completion, grammar highlighting, debugging tools, variable explorers, visualization tools, and others [49]. Thonny is a simple and easy-to-use IDE for Python with MicroPython support. In this section, the ESP32 module was programmed with MikroPython using Thonny IDE. Data collection software codes are shown in Figure 4.

Data Processing Software Codes

An integrated development environment called uPyCraft IDE can be preferred to program development devices in the MicroPython programming language. It simplifies firmware development and code debugging [49]. UpyCraft IDE is designed specifically for use with MikroPython. In this section, the ESP8266 module was programmed with MikroPython using UpyCraft Ide. Data Processing software codes are shown in Figure 5.

System Operating Steps

When the system data processing code is run, the IP address "192.168.43.48" seen on the screen is written to the "UDP_IP = " " " section in the data collection code to specify which address the data will be sent to. Operation of the data acquisition system: Temperature readings are taken by connecting to Wi-Fi. The data collection flow chart is shown in Figure 6. The collected data begins to be processed according to the flow chart shown in Figure 7. If the temperature value read from the transmitter is less than the measured temperature value, the system turns off the heater. If the temperature value received is greater than the measured temperature value, the heater is turned on and reaches the temperature value read on the transmitter.

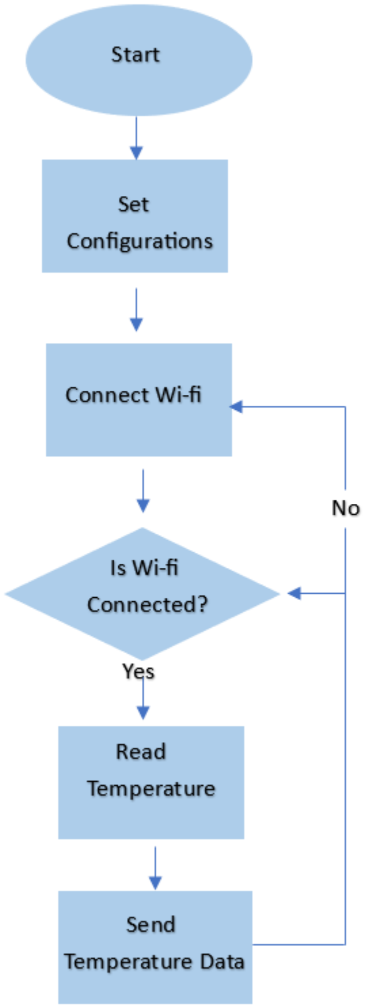


Figure 6. Data collection flow chart

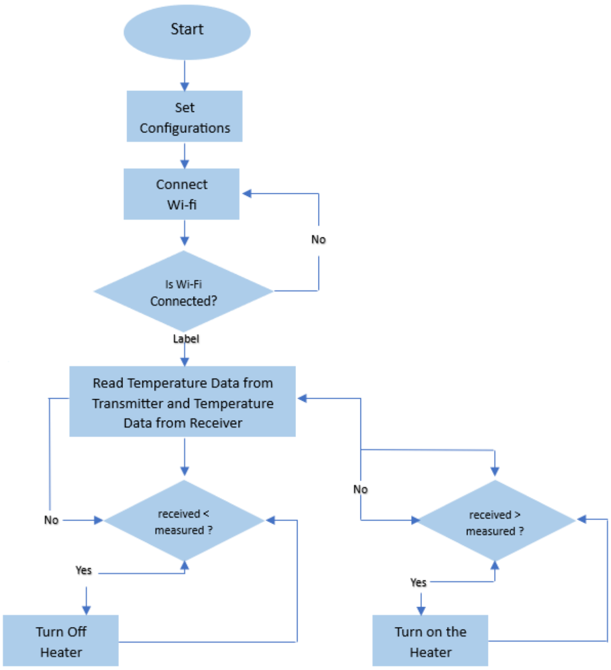


Figure 7. Data processing flow chart

4. Findings

A glove capable of real-time temperature measurement with a built-in temperature sensor, shown in Figure 8, was used. In the experiments, how temperature changes were detected and how the Peltier element reacted to these changes were examined by using a glove containing a temperature sensor. This involved recording temperature changes when hot and cold objects were touched. An experiment was conducted to measure these temperature changes when the glove touches hot and cold objects and to determine how long and how a thermoelectric element called Peltier responds to these temperature changes. Temperature values were recorded when the glove touched a hot object (e.g. a teapot at 70°C) or a cold object (e.g. chicken taken from the freezer at -14°C). It was recorded how long and how the Peltier reacted, shown in Figure 9, according to the temperature changes of the object touched by the glove.

Figure 8. Glove that can measure real-time temperature

Figure 9. Peltier that can react in real time

Soft Pneumatic Actuator Use The soft pneumatic actuator device developed by Sonar, Huang and Paik, provides realistic haptic feedback by simulating different textures and recreating the contour of various shapes in the VR environment. This device was able to simulate physical interaction with 83% accuracy. By using a similar actuator technology in our study, it could further improve tactile perception [50]. Energy Efficiency and Skin Compatibility A study by Lindsay et al, developed a vibrotactile system that increases energy efficiency and consumes less power by adapting to skin impedance. This technology offers new avenues for miniaturization and development of wearable haptic devices. In your article, by using similar energy-efficient designs, it will be possible to improve the performance and user experience of your wearable devices [51]. Imitation of Mechanoreceptors In the research conducted by Shimada, artificial haptic sensors that imitate the mechanoreceptors of human skin were developed. This work presents methods to predict fast and slow adaptation in haptic sensing, and this approach can be used to increase the sensitivity and accuracy of your wearable devices [52].

Application of Haptic Wearable Devices in Individuals with Hypothesis A review by Shull and Damian, highlights the potential of haptic wearable devices to increase functionality for individuals with sensory disabilities. These devices can be used as sensory replacement, sensory augmentation, and trainer. The use of similar devices to increase tactile perception in individuals with hypoesthesia can improve the quality of life and accelerate rehabilitation processes [4]. Haptic Performance Diagnostic Device for Children with Hypostesis A haptic performance diagnostic device developed by Chikai and Miyake is a hypostasis and/or Designed for children with symptoms of hyperesthesia. This device can be used to identify and treat tactile perception disorders by presenting a variety of tactile sensations (e.g. itching, tremors). Such devices have the potential to demonstrate practical effects and benefits for individuals with hypoesthesia, offering a similar approach to your wearable device in your article [53]. Sensory Substitution and Augmentation A study by Wheeler et al, demonstrated through rotary skin stretching examined the effectiveness of a haptic device that provides proprioceptive feedback. This device reduced aiming errors in blind movements and reduced visual demand in situations where vision was occupied. Using a similar device in your article, it can enhance the sensory perception of individuals with hypoesthesia and assist them with daily activities [54].

4.1 Analyzes

To see how the temperature changes over time, the temperature values are shown in Figure 10. Time Series Plot.

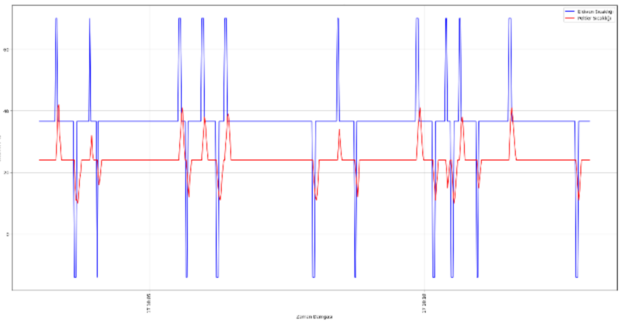


Figure 10. Time series analysis

To determine how quickly Peltier reacts to temperature changes, the time between the moment the glove touches a hot or cold object and the moment Peltier responds to this change is measured and shown in Figure 11. Response Time Analysis.

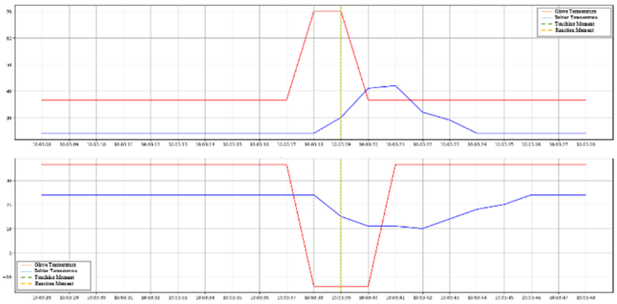


Figure 11. Response time analysis

Histograms were used to show the distributions of glove and Peltier temperature values. Temperature Distributions are shown in Figure 12.

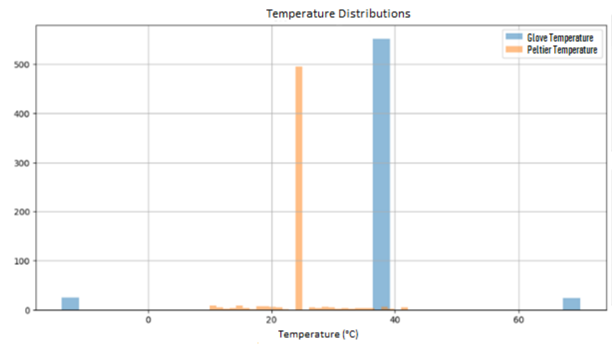


Figure 12. Temperature distributions

Glove Average Temperature	:	35.83°C
Peltier Average Temperature	:	24.00°C
Glove Temperature Standard Deviation	:	12.28
Peltier Temperature Standard Deviation	:	3.94
Glove Min-Max Temperature	:	-14.0°C - 70.0°C
Peltier Min-Max Temperature	:	10°C - 42°C
Glove and Peltier Temperature Correlation	:	0.29
Average Reaction Time	:	2.90 seconds

The relationship between temperature changes of the glove and Peltier's responses was measured. It is shown in Figure 13.

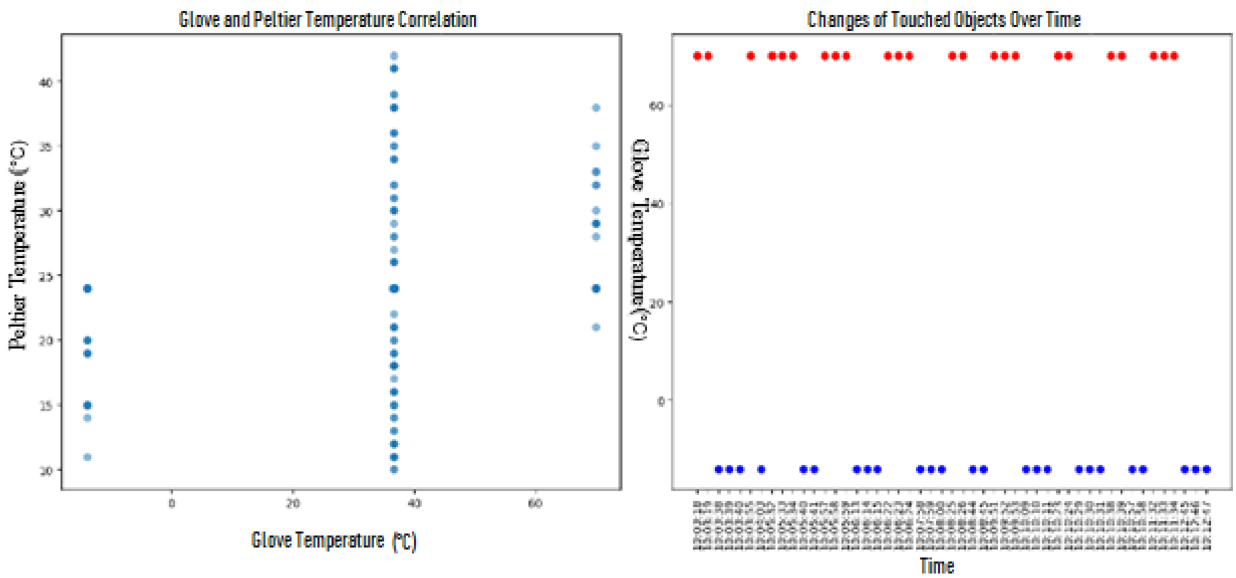


Figure 13. Correlation analysis

The data obtained were analyzed using time series graphs, response time analyzes and histograms of temperature distributions. These analyzes reveal the relationship between temperature changes of the glove and the responses of the Peltier element. In conclusion, a new model that can detect thermal noxious stimuli to accelerate the withdrawal reflex of hypoesthesia patients is proposed.

Flexible and Bi-directional Heating/Cooling Features give originality to the work. For example, Lee et al. , which provides flexible and bi-directional heating/cooling for realistic virtual reality (VR) environments, can make fast and accurate temperature adjustment with 230% stretchability. Your article demonstrates the potential of the device for use in VR applications, highlighting features such as higher flexibility and temperature adjustment sensitivity than similar devices [14]. However, while these studies generally focus on thermo-haptic feedback only on temperature perception, our current study addresses a broader spectrum of haptic sensation.

Applicability to Multiple Body Regions is important. Introduced by Maeda and Kurahashi , TherModule can be worn on multiple body parts such as wrist, arm, ankle, and neck. The device in your article has similar versatility, increasing its applicability for different use scenarios [55]. PneuMod, developed by Zhang and Sra , is a modular haptic device that has a simple, user-friendly design and can be integrated into different parts of the body. In your article, you can point out wide usage areas and easy adaptation by providing a similar user experience [10].

5. Conclusion

The thermo-haptic wearable device developed in this study and its integration with machine learning offer significant improvements for individuals with tactile sensory loss. Our main findings show that this type of device can precisely simulate temperature perception and enrich real-world interactions. In particular, the device's ability to produce real-time responses when interacting with hot and cold objects is a significant advance in the field.

In terms of practical applications, this model can play an important role in rehabilitation and daily living activities for stroke patients and individuals with other sensory limitations. The use of the device can allow these individuals to perceive their environment more effectively and therefore live a more independent life.

Our research expands the existing literature on thermo-haptic sensing and machine learning. This study has established a foundation that will guide future research and encourage the integration of these technologies into broader areas of application. In particular, it offers new opportunities for the use of wearable technologies in medical rehabilitation and virtual reality applications.

In conclusion, a new model has been proposed to detect thermal harmful stimuli using a haptic feedback stimulation system responsible for rapidly initiating withdrawal reflexes in patients with conditions like diabetes and paralysis, who over time experience hypoesthesia. The proposed model, based on the literature review conducted, represents the first endeavor aimed at designing, evaluating, and sensing through other parts of the body a thermal haptic feedback stimulation system. The experiments conducted have successfully demonstrated how the Peltier element perceives hot and cold touches made with the glove and responds to these perceptions. The reaction times and temperature change dynamics of the Peltier have been successfully analyzed through touches performed with the glove. This research has taken an important step towards improving the quality of life of individuals with tactile sensory loss, taking into account both technological innovations and practical applications. The findings of this study provide a strong basis for future technological developments and open new doors for research in this field.

Conflict of Interest Statement

There was no conflict of interest between the authors.

Statement of Research and Publication Ethics

There is no need for ethics committee permission for the edited article and there is no conflict of interest with any person/institution in the article.

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