Design of a Lightweight and Easy-to-Wear Hand Glove with Multi-Modal Tactile Perception for Digital Human

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Abstract

Within the field of human-computer interaction, data gloves play an essential role in establishing a connection between virtual and physical environments for the realization of digital human. To enhance the credibility of human-virtual hand interactions, we aim to develop a system incorporating a data glove-embedded technology. Our proposed system collects a wide range of information (temperature, bending, and pressure of fingers) that arise during natural interactions and afterwards reproduce them within the virtual environment. Furthermore, we implement a novel traversal polling technique to facilitate the streamlined aggregation of multi-channel sensors. This mitigates the hardware complexity of the embedded system. The experimental results indicate that the data glove demonstrates a high degree of precision in acquiring real-time hand interaction information, as well as effectively displaying hand posture in real-time using Unity3D. The data glove's lightweight and compact design facilitates its versatile utilization in virtual reality interactions.

Keywords: Data gloves, human-computer interaction, embedded system, virtual environment, digital human, metaverse, AR/VR/XR

1 Introduction

Human-computer interaction has reached a new age due to the rapid advancement of virtual reality integration technologies. The metaverse has garnered attention since Facebook's 2021 rebranding into Meta in 2021 [1] . The metaverse is a complex virtual world that smoothly integrates with our physical world [2, 3]. A vital aspect of the metaverse is its interaction with the physical world, combining the virtual and the real. As the metaverse evolves, the possibility of everyone having their own 3D avatars to meet their daily, professional, social, gaming, and collaborative needs in the virtual world becomes increasingly likely. The 'Metaverse' aims to create a shared virtual realm where virtual and actual realities coexist and evolve [4]. Particularly, extended reality (XR) technology—virtual reality (VR), augmented reality (AR), and mixed reality (MR)—enables this complex combination of augmented corporeal reality and virtual expanse [5, 6].

Recognition of body positions via wearable technology is a crucial aspect of continuous and natural interactions between persons and VR equipment [7]. Although vision-based posture estimation has achieved success, its effectiveness is limited in natural outside environments due to obstacles including occlusions and unfavorable lighting conditions. Furthermore, contemporary wearable gadgets frequently exhibit characteristics such as large size, heavy weight, high cost, and lack of flexibility, which make them less than ideal alternatives [8]. The demand for a skin-compatible strategy that prioritizes user comfort and incorporates flexible posture recognition in the emerging metaverse era is clearly apparent [9].

1.1 Data Glove

The selection of a glove, which is a frequently used textile item, is based on its ability to closely conform to the shape of human fingers, thereby matching effectively with cognitive reasoning. As a result, gloves can be considered an optimal medium for the manifestation of posture recognition. Given this perspective, a variety of research efforts focused on glove-based posture recognition have arisen [10]. Wu et al. presented a novel electronic glove that utilizes MXene fibers and incorporates machine learning methods. This innovative glove enables the identification of 15 distinct hand postures and allows for the remote manipulation of a robotic palm. Nonetheless, there are ongoing concerns regarding the efficient and adaptable incorporation of electronic components into gloves in a cost-effective manner. In the majority of current E-glove systems, the integration of sensor units is commonly achieved through the utilization of fiber braided or bonding with adhesive techniques. These sensor units are then connected to rigid circuit boards using traditional cables. The utilization of this auxiliary integration method results in cumbersome processes, restricts the range of hand movements, and increases the susceptibility of electrical connections between different components, so affecting the overall resilience of the system [11, 12].

1.2 Related Work

In recent years, there has been a persistent drive among researchers to improve the technological capabilities of data gloves. For example, Oliveira et al. [13] has contributed to the field by designing a specialized data glove specifically tailored for the manipulation of mechanical arms. Similarly, Lu et al. [14] have made advancements in the area of gesture detection by developing a data glove that utilizes Kinect technology. However, it should be noted that both methods employ a singular bending sensor for finger movements, hence imposing constraints on integration capabilities and resulting in noticeable disruptions during usage. According to Lin et al. [15], the architecture of the data glove includes optical bending sensors that can track finger movement in several directions. Furthermore, the 5DT fiber optic data glove, which is widely employed in the domain of gesture recognition, has received considerable scrutiny [16]. It is important to acknowledge that the production costs associated with data gloves are generally considerable, and their primary focus is on enhancing finger mobility, which consequently limits the number of available data gathering channels.

2 A Detailed Design Description for the Proposed Glove

The main module of the proposed glove is mainly divided into three parts: (a) *Design of Acquisition Circuit*,(b) *Sensor distribution and glove making*,(c) *data collection from the hardware the glove*, (d) *data representation*, and (e) *virtual scene reproduction.* We describe these in the following.

2.1 Design of a Multi-Channel Signal Acquisition Circuit

To ensure precise tracking of hand movements, our approach uses two strain gauges on each finger, positioned at the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints [17]. By measuring the bending angles of both joints, we can capture more realistic hand gestures. To achieve this, each data glove is equipped with a total of ten flex sensors. Table 1 and Fig. 1 show the MCP/PIP joints and range of angles.

The change in resistance of a bending sensor during the bending process is relatively small compared to the initial resistance, leading to low direct acquisition precision, poor accuracy, and high error rates. To address this challenge, a Wheatstone bridge circuit was constructed [18], which allowed the output voltage of the bridge to be introduced into a second-stage amplification circuit. However, the expansion of the circuit for ten bending sensors resulted in a significant increase in the hardware circuit volume of the system.

To achieve the goal of miniaturization and high integration of the glove system, the circuit was optimized. The signal amplification circuit was found to be relatively large in size and repeated frequently, prompting the design of a multi-channel traversal loop circuit that divided the circuit into three parts: signal amplification, signal selection, and adjustable matching resistors. In the signal selection circuit section, the switch conduction properties of composite MOSFET tubes were utilized [18]. The MOSFET tube D pole was connected to one end of the bending sensor, and the S pole was connected to the other end of the bending sensor, which was then connected to the Wheatstone bridge circuit. The switch control of the MOSFET's G pole was achieved using the excess general IO port on the single-chip microcomputer. The circuit diagram is shown in Fig. 2.

When the I/O port outputs a high voltage, the MOSFET switch is turned on, allowing the D and S poles to conduct and the curvature sensor to be connected to the amplification circuit for data collection. Conversely, when the I/O port outputs a low voltage, the circuit is in a high impedance state, equivalent to an open circuit, and does not participate in signal acquisition. The control process is illustrated in Fig. 3. The I/O control is cycled to sequentially connect ten curvature sensors to the amplification circuit, enabling the measurement of the curvature of ten joints.

The utilization of a scanning circuit has reduced the required number of ADC channels and minimized the need for redundant complex circuitry, thus significantly saving valuable circuit board space. In addition, a variable resistor has been integrated into the sensor amplification circuitry, as illustrated in Fig. 2, to match the scanning circuit and achieve independent amplification factor configuration for sensors with varying degrees of bending.

2.2 Sensor distribution and glove making

The glove is made using synthetic suede material, which offers a specific level of stiffness and incorporates all modules and circuits for ease of wearing. The fingertips of the glove are equipped with pressure and temperature/humidity sensors, while the corresponding finger joints are outfitted with bend sensors, allowing for sufficient space for movement. The signal lines of the sensors are uniformly extended and linked to a specialized circuit board positioned at the central region of the dorsal side of the hand, which is powered by a lithium battery. The implementation of integrated design successfully mitigates the hindrance caused by hand movements when using gloves. Fig 4 depicts the process flow of the glove, while Fig. 5 presents the physical appearance of the glove.

The near-end configuration comprises a mechanical arm and a human operator. The robotic arm is outfitted with our proprietary tactile sensing glove, whereas the operator use our tactile

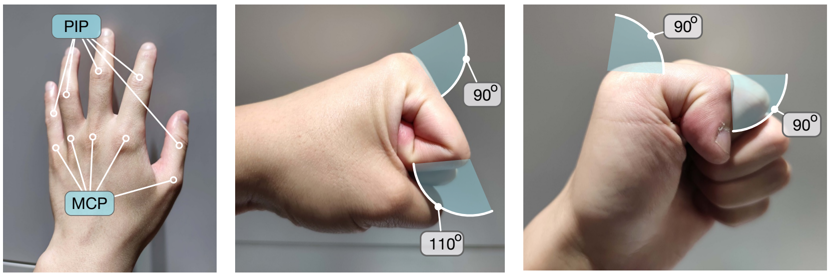


Figure 1: MCP/PIP position and range of angles.

Table 1: Range of angles for finger joints

Fingers	**Range of Angles (°) for MCP Joint**	**Range of Angles (°) for PIP Joint**
Thumb	0–90	0–90
Index, Middle, Ring, Little	0–90	0–110

sensing glove. The data glove we have developed encompasses many features for the acquisition of position, orientation, temperature, humidity, and pressure data. The term ”glove part” is designated as a sort of mid-range information collection. Ultimately, remote replication is accomplished by means of Bluetooth connectivity. The process of remote replication encompasses several key components, namely the replication of the wearer's perception, the reproduction of virtual behaviors inside the virtual world, the duplication of movements performed by the robotic arm, and the analysis of behavioral logic using stored hand motion data.

2.3 *Data Collection from the Hardware*

We obtain raw data from the flex sensors, pressure sensor, and temperature and humidity sensor.Afterwards, we transmit the collected data to a personal computer. In the following, we discuss the main units and their functionalities.

2.3.1 Initialization

As a first step, we need to initialize the pins of the microcontroller and the sensors used. During this process, the Bluetooth modules will be paired with input/output (I/O) pins to identify the connection status. If the Bluetooth module is in an unconnected state for a long time, the configuration pin is pulled down to enter configuration mode, and `AT` commands are sent via a serial port to set the master-slave relationship, communication protocol, communication mode, Bluetooth device name, transmission baud rate, communication passwords. A code snippet is as follows:

```
AT+ROLE=0     #Bluetooth slave mode
AT+ROLE=1     #Bluetooth master mode
#(Our glove is master and computer
#is slave mode)
AT + CODE = 0
# Bluetooth connection mode
#in discovery state
AT+PSWD=1234
#Bluetooth pairing password is 1234
AT+UART=460800,0,0
#Bluetooth communication
#serial port baud rate is 460800,
#stop bit is 1 bit, and no parity bit
```

Afterward, we restart the entire module to complete the above setup. Finally, when the onboard LED starts blinking, it indicates successful program initialization and Bluetooth pairing.

2.3.2 Data Collection

Data Acquisition of the Glove Hardware System involves the initialization of the chip system, utilizing the built-in multi-channel ADC of the chip for collecting data from pressure, flex, temperature and humidity sensors. The selected

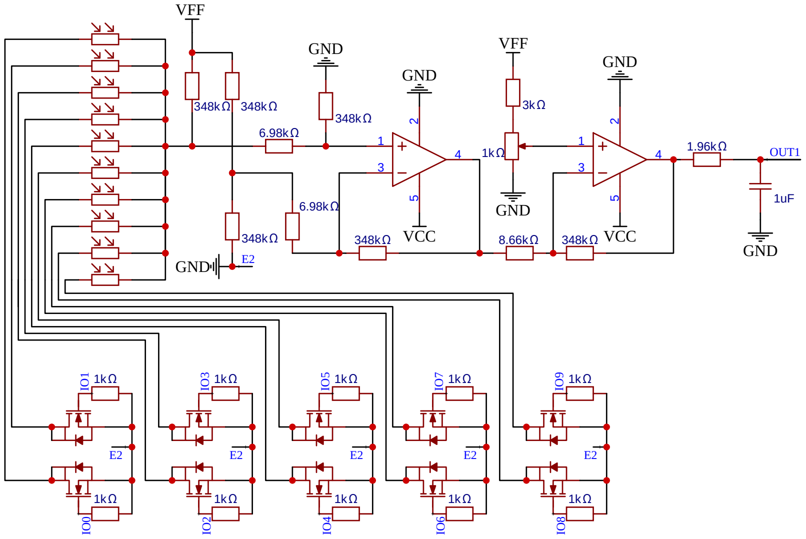


Figure 2: Circuit Diagram.

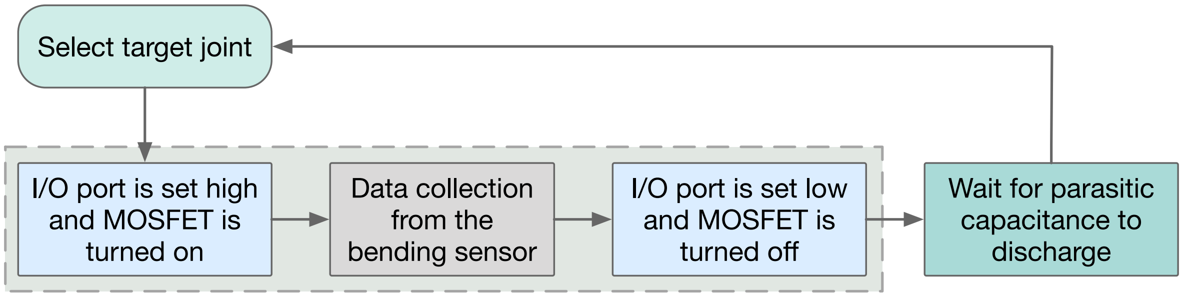


Figure 3: Traversing cyclic collection process.

chip features two 12-bit successive approximation ADCs, with five pressure sensors and one temperature and humidity sensor individually connected to dedicated acquisition channels, and ten flex sensors sharing a single acquisition channel through a polling circuit. The two types of sensors are collected under different ADC modes. The voltage acquisition of the pressure sensors is performed in scan mode, simultaneously outputting data from all five sensors, while the voltage acquisition of the flex sensors is conducted in single conversion mode, sequentially collecting voltage data from the ten sensors.

For the data acquisition of the temperature and humidity sensor, the I2C communication mode is used. The glove system utilizes software I2C communication, ensuring compatibility with different microcontrollers and facilitating portability. The data are transmitted through the analog SDA line to the chip and stored in an array.

In our hardware system, data collected by sensors is transmitted to the host computer system through a configured Bluetooth module. Data are sent in a specific format consisting of a header for the data frame, data flags, contact force data, temperature and humidity data, intermediate positions, joint bending angle data, data end marker and a checksum. The data are transmitted in hexadecimal format via Bluetooth to the PC end. The data acquisition process of the system is illustrated in Fig. 6.

2.3.3 Dataframe Structure

Fig. 7 shows the dataframe structure, where we represent data in hexadecimal values. The first two bytes of the dataframe structure denote the frame header, and the third byte represents the total length of the dataframe. The fourth to 13th bytes contain pressure sensor data from five

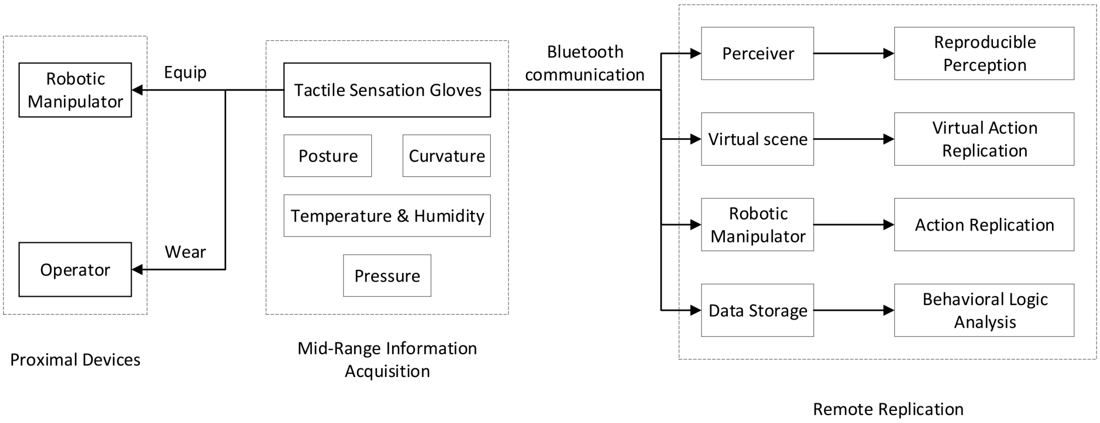


Figure 4: Block diagram of proposed glove.

pressure sensors, with every two bytes representing the data from one pressure sensor. The 14th and 15th bytes contain data from the temperature and humidity sensor. Data from bending sensors are captured in bytes 16 to 25, with each sensor represented by one byte of data. The 26th to 31st bytes contain data from the gyroscope, capturing x-y-z angle data and acceleration. Finally, the last byte of the frame is the checksum, which is used to verify the dataframe's integrity.

2.3.4 Wireless Data Transfer

The glove's wireless transmission module uses the HLK-B40 Bluetooth transmission module, which integrates master and slave capabilities. This module wirelessly sends the captured data from the glove to a computer via a serial interface protocol. One of the paired Bluetooth modules acts as the master and is soldered and integrated into the glove. The other module is connected to the computer via USB. It should be noted that all Bluetooth configurations can be saved even when the device is turned off. When the device is turned on, the module is paired and ready for data transfer.

2.4 Data Processing and Representation

$$\begin{cases} C_1 + C_2 + \cdots + C_{m-1} + C_m = 1 \\ C_1 < C_2 < \cdots < C_{m-1} < C_m \end{cases} \tag{1}$$

The longer the queue length m is, the greater the delay in the output signal and the weaker the sensitivity. For this system, we set the queue length to $m = 4$. Therefore, the calculation of the new sampled data at each time step is as follows:

$$\bar{U_n} = \sum_{i=0}^{3} C_{4-i} \cdot U_{n-i}\,. \tag{2}$$

The temperature and humidity sensor transmits data via I2C [19], which consists of 20 bits of temperature data (ST) and 20 bits of humidity data (SRH). These data are then converted into actual temperature values (T) and humidity values (RH) as follows:

$$T[°C] = \left(\frac{S_T}{2^{20}}\right) \cdot 200 - 50$$

$$RH[\%] = \left(\frac{S_{RH}}{2^{20}}\right) \times 100\%$$

2.5 Designing Virtual Environments in Unity3D

The virtual scene design in this study is implemented through the utilization of the Unity 3D software.The engine effectively emulates the principles of real-world physics, hence enhancing the authenticity of the simulation. Individuals have the ability to import three-dimensional (3D) models that have been created using software such as 3D Max or other modeling tools.

Figure 5: Our glove with bending (flex) sensors, pressure sensor, and temperature and humidity sensors.

Alternatively, they can make use of Unity 3D's pre-existing model collection in order to construct the virtual world they desire [20]. Subsequently, explicit directives are formulated to facilitate the execution of dynamic activities by assigned entities. In addition, the software provides assistance for the building of graphical user interfaces (GUIs) specifically tailored for 2D scenarios, addressing the requirements of users in terms of graphical interface design.

This paper focuses on the design of a virtual scene, which consists of three essential components: the *communication module*, which receives hand information data from lower-level data gloves; the *virtual hand control module*, which creates virtual hands to replicate and perform user hand actions; and the *GUI interface*, which facilitates serial port connections, presents fingertip pressure values, and represents finger joint flexion.

The primary design principle underlying the segment of serial port communication entails the configuration of diverse characteristics associated with the serial port connection. These parameters encompass the port number, baud rate, stop bits, and parity bits. The designated API function `new SerialPortSetting()` is utilized to open the corresponding serial port and retrieve glove data. This data is then decoded and stored in specific arrays that represent finger flexion data and fingertip pressure data [21]. Various objects present in the scene utilize specific arrays of data, resulting in the production of appropriate animation effects. This process enables the instantaneous reproduction of user hand movements and the immediate reproduction of fingertip pressure. Fig. 8 illustrates some of the examples.

```
sp = new SerialPort(portName,
baudRate, parity, dataBits);
#Receiving perceptual glove data
#via the serial port.

sp.Read(buffe, 0, count);
#Defining buffer arrays to receive
#data
#transmitted through the serial port.

Little_1.localRotation =
Quaternion.Euler(L1,0,0);
#Driving the corresponding joint
#bending of the virtual hand
#(based on real hand joint bending
#data.)

txt_msg1.text += M_F.ToString("0")
+ "N";
#Modifying the numerical values in
#the fingertip
#pressure text box based on changes.
```

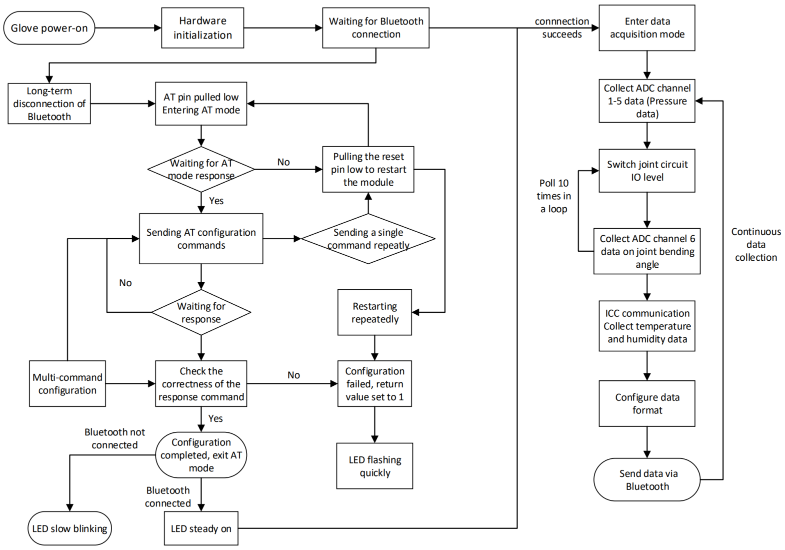


Figure 6: The overall data acquisition process.

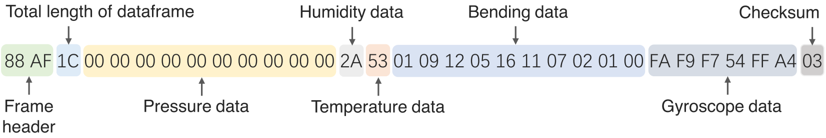


Figure 7: Dataframe structure.

3 Results and Discussion

We conduct a comprehensive testing. The testing scenarios involve the examination of interactions within diverse real-world conditions, including bending, temperature, and pressure environments, with the objective of faithfully reproducing these interactions.

3.1 Bending Data

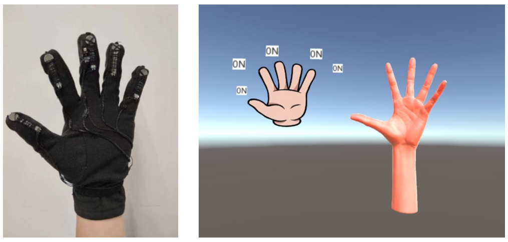
The bending degree sensor located at the PIP joints of the index finger was selected. With the MCP jonts of the index finger kept stationary, the PIP angle was gradually bent from 0° to 90° in increments of 30°. The test model was fabricated using advanced stereolithography (SLA) 3D printing technology. Its specific structure is depicted in Fig. 9. This model serves as an ideal experimental platform for evaluating the performance of the bend sensor. The testing process is illustrated in Fig. 10. The voltage data captured by the glove system from the bending degree sensor in the bent state is shown in Fig. 11. Test participants wore the data gloves proposed in this paper for a hot cup grasping experiment. Fig.12 illustrates the state diagram of grasping a hot cup while wearing the perception gloves. Additionally, Fig.13 and 14 display the data collected at the PIP and MIP joints, respectively, during the process of grasping the hot cup.

3.2 Pressure Data

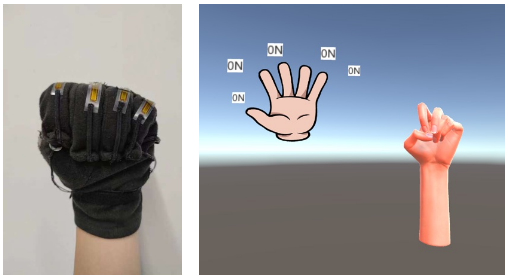
Test participants conducted pressure tests using the SJ-30N force gauge equipped with a load cell, measuring sensor voltage values. The testing process is depicted in Fig. 15. In Fig. 16, we show the relationship between the applied pressure and the average circuit output voltage with a curve fitting toolbox (considering a third-order function) in MATLAB. And Fig. 17 depicts the pressure data during hot cup grasping.

3.3 Temperature Data Testing

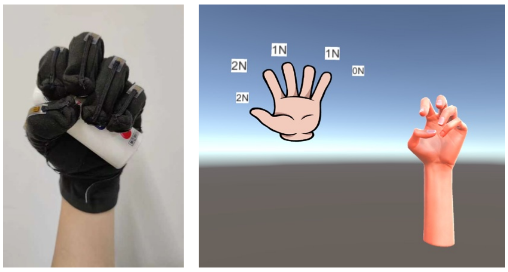
During the hot cup grasping experiment, participants utilized the perception gloves to grasp a cup containing hot water. The temperature data collected by the gloves is depicted by the red



(a) Without any object holding, palm open



(b) Without any object holding, fingers closed



(b) Object holding

Figure 8: Examples of the tactile reproduction in Unity3D.

curve in Fig. 18. Room temperature is indicated by the gray dashed line in Fig. 18. When participants used the perception gloves to grasp an ice pack, the temperature data collected by the gloves is illustrated by the blue curve in Fig. 18. The experimental procedure is shown on the right side of Fig. 18.

4 Conclusions

In this paper, we have presented a comprehensive design description of a data glove that enables real-time collection of temperature and humidity, finger pressure, and bending data. The data interface that has been suggested exhibits the capability to represent alterations in values with a near real-time effect visually. In addition, we utilize the Unity3D program to create a simulated hand activity environment, which serves as a visual representation of various hand movement postures. Specifically, our designed data glove exhibits better capabilities in capturing the temperature, angles, and pressure of the human hands, as compared to existing data gloves. Our proposed approach involves implementing a multi-channel cycle acquisition method to enhance the portability of the glove and thus obtain precise finger morphological data. Finally, the experimental results indicate that the data glove exhibits precise data acquisition, reliable reproducibility, and robust repeatability throughout its utilization. This research aims to establish a robust framework for facilitating highly integrated interactions between physical entities and their digital counterparts within the metaverse.

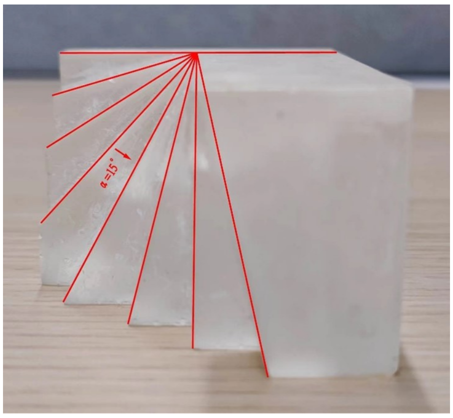


Figure 9: Staircase-like Bending Angle Testing Model

Figure 10: Bending Sensor Angle Testing Experiment Figure

However, the data gloves proposed in this study still have limitations in capturing hand information. The number of tactile sensors on the hands is extensive, extending beyond the per-

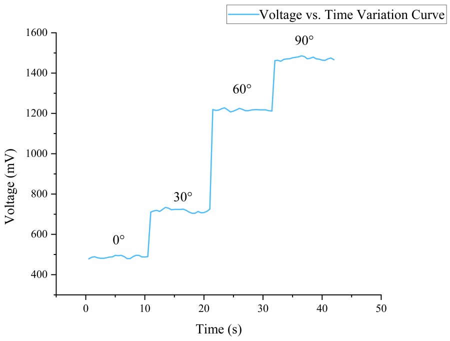


Figure 11: Bending Angle Test Data

Figure 12: Experimental Process Diagram of Hot Cup Grasping

ception acquisition channels discussed in this paper, such as roughness, among others. Expanding the channels and perspectives for hand perception can offer more options for subsequent human-computer interaction methods. A comprehensive data glove should be the future research direction for data gloves.

Another limitation of the data gloves in this study is that they can meet the accuracy requirements for most adults. However, for small-sized individuals, such as children, the accuracy of data collection during human-computer interaction while wearing the data gloves designed in this paper may decrease to a certain extent. In the future, adjusting the design to accommodate different sizes of data gloves can meet the needs of diverse user groups for human-computer interaction.

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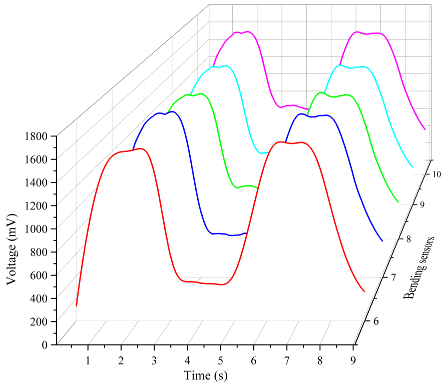

Figure 13: Data of PIP Joint Flexion During Hot Cup Grasping.

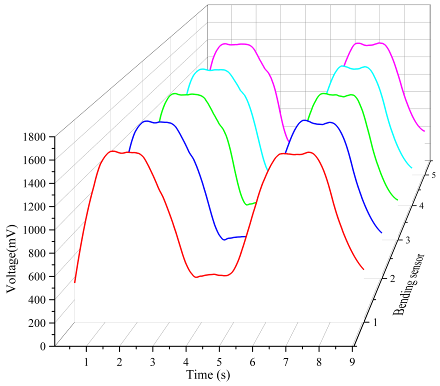

Figure 14: Data of MIP Joint Flexion During Hot Cup Grasping.

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Figure 15: Pressure Sensor Testing.

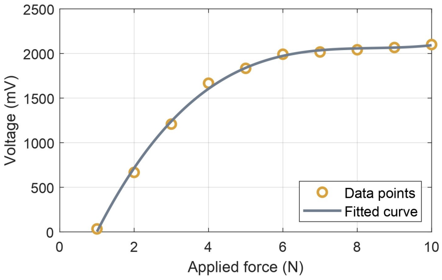

Figure 16: Fitted Curves of Pressure and Voltage Data.

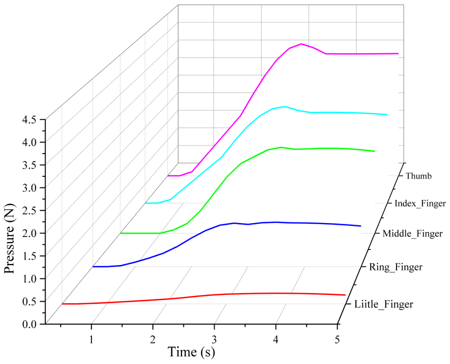

Figure 17: Pressure Data Graph During Hot Cup Grasping.

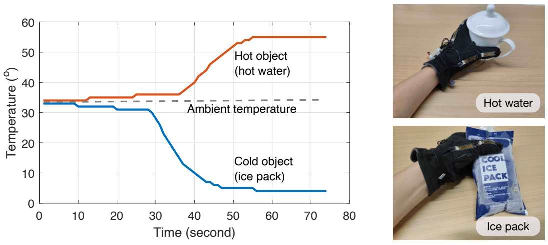

Figure 18: Temperature data.

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