A Thermal and Vibrational Feedback Glove Based on the Tactile Characteristics of Human Hand Skin

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\textbf{ABSTRACT} As an important method for humans to perceive their environment, touch has not been fully integrated into virtual reality technology. Existing tactile feedback devices have the problem of being large and expensive, and most studies have not explored the ability of the affected area to distinguish an external stimulus, thus it is difficult to perform natural human-computer interactions. This article describes the development of a device that can transmit multimodal tactile information in accordance with the characteristics of human hand skin perception during a human-computer interaction. The device has 10 miniature vibrators ($\Phi = 10 \text{ mm}$, $d=2.7 \text{ mm}$) and 2 semiconductor refrigerators ($23 \text{ mm} \times 23 \text{ mm} \times 4 \text{ mm}$), which can achieve temperature and vibration feedback. First, the structure and working principle of the device were introduced, and the device’s performance was analyzed. Subsequently, an experiment based on the perception characteristics of human hand skin was designed. The experiment determined the vibration level (I-5), heating level (I-IV), and cooling level (I-III) that are consistent with the perception characteristics of the hand skin. Finally, a chemical experiment was designed to test the performance of the device. The results of the experiment showed that 92% of the volunteers thought the device had a higher sense of authenticity and immersion than the traditional virtual reality experience.

\textbf{INDEX TERMS} Tactile feedback, temperature, vibration, virtual reality.

\section{I. INTRODUCTION}

With the rapid development of computer technology, virtual reality (VR) technology has been widely used in education, medical treatment, entertainment and other fields [1]. Cai and Shi [2], Yang [3], and Moore [4] integrated virtual technology into a teaching system and developed virtual teaching systems for different fields [1]. Moro et al. [5] verified the effectiveness of virtual technology by analyzing its application in medical teaching. Brinson [6] and Azar and Sengülec [7] comprehensively compared learning using traditional experimental operations and nontraditional laboratory learning based on virtual and remote technologies. The results showed that VR technology has a positive effect on students’ performance and learning attitude and is widely welcomed by students.

However, these studies focus on the feedback from visual and auditory information, and only rarely involve tactile interaction information. Moreover, these studies do not perform in depth exploration of the human body’s perception of tactile information. As one of the five senses of a human’s object characteristic and movement perception, tactile senses play an important role during the interaction with the world around us [8], [9]. Ernst and Banks [10] pointed out that “the human brain uses tactile information and visual information to mutually modify, and in some cases, perception is obviously affected by tactile sense”. Practice shows that visual and auditory stimulation alone cannot convey complete environmental information to user [11]. At the same time, physiological studies have pointed out that human touch is generated by sensory receptors under the skin, and these sensory receptors in different parts of the human body vary greatly in type and quantity, resulting in different perceptions and in the spatial discrimination of tactile information.
Inappropriate stimulation may cause dislocation between tactile and other senses, giving users an illusion [12], [13].

These problems not only hinder the further development of human-computer interaction but also directly affect the three essential characteristics of VR systems: interaction, immersion and imagination. Therefore, it is necessary to add tactile feedback that is in line with human body perception characteristics during human-computer interaction so that users can truly experience the virtual environment and so that VR technology can be further developed and applied.

Haptic feedback refers to the use of computers and specific algorithms to calculate the interaction between the user and the virtual environment. Then, haptic feedback devices reproduce this interaction to the user by stimulating various sensory receptors in the skin so that people can truly feel the tactile information in the virtual environment. Current research has developed various types of tactile information, such as vibration, temperature and force feedback, using different actuators.

In the relevant research work of vibration feedback, Chen et al. demonstrated that different vibration signals could be used to express different emotions [14]. Zeng et al. [15] developed a device that can be placed around the eye and uses a flexible vibrator (12 mm × 12 mm × 6 mm) to generate vibration sensation. Through two virtual scenes, the role of vibration in improving VR immersion was studied. Borja et al. [16] designed a tactile stimulation glove for sports rehabilitation. This glove could detect finger bending through the sensor on the glove and generate vibration stimulation with ten vibration actuators installed on the finger and palm. Yu et al. [17] developed a noninvasive device that can cover the skin surface, and this device was able to simulate vibration and tactile sensations by adjusting 32 actuators. Ninu et al. [18] developed a tactile stimulation device that could independently adjust the amplitude and frequency of vibrations. Dharma et al. [19] proposed a tactile vest consisting of 60 vibratory tactile actuators, and this vest could generate a variety of tactile modes with complex spatial and temporal characteristics. Yannier et al. [20] developed the “FeelSleeve” tactile device that uses a piezoelectric drive to generate vibration by adjusting the exciting electric field of the audio exciter.

In related temperature tactile feedback research, Chen proposed that the temperature is one of the important factors when identifying a material [21]. Ho et al. verified the role of temperature information in material identification and positioning [22]. Chen et al. [23] designed a temperature tactile sensing module based on a composite Peltier module and analyzed its feasibility in the field of navigation for visually impaired. Peiris et al. [24] integrated a Peltier device into an Head Mounted Display (HMD) device to provide temperature feedback directly to the user’s face, and this device improved immersion during interaction. Peng et al. [25] used thermal feedback to simulate a sensation of penetrating the body.

The current research can achieve single tactile feedback in different situations, but current technology is still insufficient to realize authentic human-computer interaction. Song et al. [26] designed a wristband-type device that uses vibration, temperature and pressure change to as a reminder. The device was divided into two parts: one part that provides a single vibration and a cold and hot temperature change and the other part provides a pressure change.

Ranasinghe et al. [27] developed a head-mounted tactile sensing device that can sense smell, wind and temperature. They added a small oil bottle to the back of the helmet, used a piezoelectric diffuser and catheter to spray oil up the nose, and used a tiny fan to blow the volatile oil up the nose. A fan was also added to the lower part of the helmet to blow airflow into the neck and face to create a sense of wind, and a semiconductor refrigerator was installed in the neck area to create a sense of temperature change.

Wolf et al. [28] developed a tactile feedback device that simulated vibration sensations and temperature change by installing a semiconductor refrigerator and a miniature vibration plate on the side of the HMD device that contacts the facial skin. Then, the performance of the device was studied through user experience. The results showed that the device had a better user experience in game scenarios.

One of the existing problems of multiple tactile feedback devices is that these systems are relatively complicated. Similar to the small devices studied by Song, there is a problem in that the number of tactile actuators is limited, which, in turn, limits the achievable tactile information. At the same time, due to the wide action area of actuators, the research has stopped at the construction of tactile feedback devices. The perception characteristics of the action area are not discussed in detail. Therefore, it is difficult to clearly establish a mapping relationship between the action of the actuators and the resolution of skin perception. These deficiencies limit the further application of multiple tactile feedback devices.

In this article, an innovative device is designed to realize multiple tactile feedback, and this device is combined with an ordinary glove without additional auxiliary equipment. Using 12 actuators, multilevel tactile changes consistent with hand perception characteristics are determined through the results of user perception experiments. This device enhances the realism of the virtual environment and provides a feasible solution for multitactile feedback during human-computer interaction.

II. REALIZATION OF TACTILE FEEDBACK DEVICE

A. OVERALL DESIGN

The tactile glove designed in this article include temperature and vibration feedback and was divided into 6 functional parts: microcontroller module, actuator module, power module, Bluetooth communication module, temperature detection module, and temperature display module. These parts together provide a variety of functions including supplying the power for the equipment, downloading the program, wireless communication, temperature acquisition, actuation and other actions. The structural diagram of the functional modules is shown as Figure 1. In this figure, the red name
indicates that the module is powered by the power module; otherwise, the module is controlled by the microcontroller. This work creates an integrated control circuit board (70 mm × 60 mm) that integrates the power regulator/buck circuit, the microcontroller module, the actuator drive circuit, etc. A pluggable structure is used to connect the actuator for different applications. Furthermore, 12 3.5-mm audio interfaces are installed on the integrated control circuit board to connect to the actuator. This pluggable design can realize actuator movement according to the actual demand and facilitate the maintenance and replacement of the faulty actuators. Its small size allows this control board to fit perfectly on the arm. Figure 2b shows the integrated control circuit board. Lv1-lv5 and RV1-RV5 are miniature vibrators placed on the left and right hands, respectively, and LP and RP are semiconductor refrigerators placed on the left and right hands, respectively, as shown in Figure 2a.

Considering that both hands are arranged with actuators, using the same two sets of integrated control circuit boards will undoubtedly increase the cost. Therefore, this device uses a small relay board (as shown in Figure 2c). The small relay board is placed on the wrist, a 3.5-mm audio interface is welded on the relay board, and a 50-cm audio cable is used to connect the integrated control circuit board and the relay board. The actuator placed on the hand is connected to a 3.5-mm audio plug and is then connected to the relay board. Thus, connecting the integrated control circuit board to both hands is done in a way that allows both hands to move freely. The connection diagram is shown in Figure 2a. A picture of the actual device being worn is shown in Figure 2f and Figure 2g.

**B. WORKING PRINCIPLE**

The tactile glove with temperature and vibration feedback designed in this article is applied to the system shown in Figure 3. The system can be divided into two parts: the virtual scene platform of the upper computer and the platform of the lower computer. All the functional structures of the lower computer platform are integrated into the tactile glove to mainly achieve vibration and temperature information feedback. The virtual scene of the upper computer can be run on a PC or mobile device and can wirelessly communicate with the lower computer platform via a Bluetooth module. Moving objects in the virtual scene by user operations not only achieves audio-visual changes but also creates vibration and temperature changes that are generated by the actuators to simulate tactile experiences in the virtual environment.

When creating the virtual scene using the upper computer, the temperature and vibration change data related to the virtual scene are written in the script. When the user manipulates objects in the virtual scene using key interactive means, the background program generates vibrations and temperature information requirements according to the user’s operation, and sends this information to the microcontroller of the lower computer platform’s integrated control circuit board via the Bluetooth communication module according to the preset
III. FUNCTIONAL MODULE DESIGN OF TACTILE GLOVE

A. BLUETOOTH COMMUNICATION MODULE

The communication module adopts paired Bluetooth, through which the upper computer sends a series of control data to the lower computer. The frame and specific information about the control data are shown in Table 1 and Table 2.

The control data frame for communication between the upper and lower computers determined in the system design is a 16-digit decimal number, which corresponds to 10 miniature vibrators and 2 semiconductor refrigerators arranged on both hands. The independent action of 12 actuators can be realized, and vibrations and temperature stimulations of different intensities can be generated. Furthermore, the semiconductor refrigerator can produce both cold and hot temperature changes on a single side.

In detail, the action mode of semiconductor refrigerator is divided into 3 types: mode 0 indicates neither cooling nor heating; mode 1 is cooling mode; and mode 2 is heating mode.

The action levels of the semiconductor refrigerators and the miniature vibrators are determined according to the results of the perception experiment in section IV of this article. The action intensity varies depending on the level.

B. POWER MODULE

In this device, an independent power supply (555060, ZONCELL, China) is used to provide power for the functional modules, such as Bluetooth communication, microcontroller, temperature detection, temperature display, and semiconductor refrigerators. Power supply is a rechargeable polymer lithium battery (75 mm × 50 mm × 11 mm), its weight is 84 g, its capacity is 5000 mAh, its nominal voltage is 5 V (±0.5 V), and its maximum working current is 1.2 A. Voltages with amplitudes of 5 V and 3.3 V can be output stably through the functional circuit.

Combined with the action scene of this device, under a maximum current output, the battery life of the power supply is more than 4 hours.

C. TEMPERATURE DETECTION AND DISPLAY MODULE

The temperature detection uses the form of negative temperature coefficient thermistor and constant value resistance...
in series. The microcontroller processes the collected information to calculate the measured temperature value. The temperature display uses a 0.91-inch OLED screen (Waveshare Electronics, China), on which the microcontroller will display the calculated temperature value. The display diagram is shown in Figure 5.

**FIGURE 5.** OLED display diagram.

FIGURE 5. OLED display diagram.

D. ACTUATOR MODULE

In this device, the action of the actuators is controlled by adjusting the output voltage of the microcontroller. Pulse width modulation (PWM) is used to adjust the output voltage of the microcontroller. The I/O port voltage of the microcontroller is 5 V, and the output PWM signal frequency is approximately 500 Hz. An oscilloscope is used to detect the microcontroller output port waveform, and the output waveform with a 60% duty cycle is shown in Figure 6.

**FIGURE 6.** D = 60%.

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1) MINIATURE VIBRATOR

The miniature vibrator (1027, ASLONE, China) is a kind of micro DC motor. Its core vibrating component is a rotor equipped with an eccentric weight. The structure is shown in Figure 7. After the element is energized, the coil is subjected to a magnetic field generated by the permanent magnet, which drives the rotor with the eccentric weight to rotate in the magnetic field to generate an excitation force.

The excitation force $F$ generated by the element can be express as the following:

$$ F = m \cdot r \cdot \omega^2 $$

(1)

where $m$ is the mass of eccentric weight; $r$ is the rotation eccentricity; and $\omega$ is the rotation angular velocity.

The external pins of the miniature vibrators are connected to the output pins of the microcontroller, as shown in Figure 8. PWM is used to adjust the equivalent output voltage.

**FIGURE 7.** Structure schematic of the miniature vibrator: 1. upper shell 2. eccentric weight 3. permanent magnet 4. bottom shell 5. FPCB 6. rotating shaft 7. bottom rotor 8. Coil.

**FIGURE 8.** Control diagram of the miniature vibrators.

In this work, the vibration acceleration is used to indirectly measure the excitation force. The relationship between the vibration acceleration and the excitation force is expressed as the following:

$$ a = \frac{F}{M \cdot g} $$

(2)
where $F$ is the excitation force; $M$ is the mass involved in the vibration; and $g$ is the acceleration due to gravity.

An acceleration sensor is used to collect the vibrational acceleration data from the miniature vibrators when the output voltage PWM duty cycle is 60% and 100%, as shown in Figure 9 and Figure 10.

The acceleration values of vibrators are different when different output voltages are used. This indicates that the excitation force generated by the eccentric structure is different and can be used to convey different vibration sensations.

2) SEMICONDUCTOR REFRIGERATOR
The semiconductor refrigerator (TES1-7102, BJ peltier TE Cooling Equipment Co., Ltd, China) is made using the Peltier effect and uses a semiconducting material to change the direction and amplitude of the current passing through the material, and the element can create a temperature change.

In practical applications, a large electric current is required if the temperature change is to the degree such that the skin can feel the change. Considering that the control signal output of the microcontroller is usually only a microcurrent and that the device needs to achieve a temperature change in both hot and cold directions on a single side of the refrigerator, an H-bridge is used. The switch element on the bridge arm uses MOSFET which is suitable for high frequency action, to quickly adjust the amplitude and direction of the current passing through the semiconductor to achieve the temperature change.

The semiconductor refrigerator is a thin element (23 mm $\times$ 23 mm $\times$ 4 mm) with ceramic materials on both sides. To better measure its heating or cooling performance, one side was coated with heat dissipation grease, and a heat sink (20 mm $\times$ 20 mm $\times$ 6 mm) was installed. A control signal PWM duty cycle of 20%, 40%, 60%, 80% and 100% are used to create a corresponding equivalent output of 1, 2, 3, 4 and 5 V, respectively. Under the different output voltage conditions, the temperature change on the other side is measured for the next analysis. During the experiment, the room temperature was maintained at 29°C, and the temperature sensor automatically recorded data per second.

In heating mode, the increasing temperature curve of the semiconductor refrigerator is recorded, as shown in Figure 11.

In cooling mode, the decreasing temperature curve of the semiconductor refrigerator is recorded, as shown in Figure 12.

In heating mode, considering the pain threshold of the human body [29], the temperature increase is limited to 47°C for safety reasons. At the same time, to ensure that different increasing temperature rates can transmit different information, this article determines that the interrupt should begin when the temperature increases to 47°C. A PID algorithm is used to control the temperature to maintain this temperature. Figure 13 shows the temperature-time figure of a stable
The semiconductor refrigerator has satisfactorily fast performance and can not only be used for heating and cooling the system but can also be used in future work requiring temperature stability.

IV. TACTILE STIMULATION INTENSITY IDENTIFICATION EXPERIMENTS

Vibration tactile perception and temperature tactile perception can transmit emotion [32], [33]. Stimuli having different intensities represent different information, so it is very important to be able to correctly distinguish between vibration and temperature stimulations of different intensities. We conducted vibration and temperature intensity perception and identification experiments using this device to explore people’s ability to judge the form of vibration and temperature tactile stimulations. These experiments were performed to provide reference when setting the action level of this device.

A. PARTICIPANTS

A total of 10 right-handed healthy subjects participated in the experiment (5 females, age: 24.5 ± 1.58 years, mean ± SD). The subjects had no sensory disorders and had not previously participated in a similar experiment. The experimental procedure was approved by our university ethical committee.

B. EXPERIMENTAL ENVIRONMENT

The experiment was carried out in a normally lit room with an ambient temperature of 29°C. Considering that the device has a certain sound during operation, which can have a certain influence on the experiment, we required subjects to wear ear muffs during the experiment to eliminate the influence of sound. Communication was not allowed during the experiment, and no information related to the experiment, such as whether the answer is correct, was disclosed to the subjects during the experiment.

C. EXPERIMENTAL METHOD

1) VIBRATION INTENSITY PERCEPTION AND IDENTIFICATION EXPERIMENT

Vibration tactile stimulation was divided into five levels (the PWM duty cycles corresponding to the output voltages were 20%, 40%, 60%, 80%, and 100%), which corresponded to 5 intensity types: very weak (A), weak (B), medium (C), strong (D), and very strong (E). The stimulus presentation time was 5 seconds. If the stimulation time is too long, the subjects will become numb in their hands and will be easily distracted. If the time is too short, the subjects might not respond.

In the experiment, the subjects wore the device on their right hand. The researcher selected one of the five tactile stimulation levels and presented it to the subjects’ right hand. The subject responded with the intensity level that corresponded to the vibration stimulation he perceived, and the researcher recorded the subject’s responses. The experiment was divided into two rounds according to the training situation of the subjects. In the first round, the subjects were directly asked to select the tactile state perceived by the hands without training. Subjects in the second round were trained first. The content of the training is that the participants experience different levels several times and were told the intensity level corresponding to the tactile stimulation they felt, and they then participated...
in the experiment. There were 5 stimulus intensities, and each stimulus was tested 6 times. Each subject was tested 30 times in each round with a random presentation order.

2) TEMPERATURE INTENSITY PERCEPTION AND IDENTIFICATION EXPERIMENT

Temperature stimulation has 2 changing directions: heating and cooling. In this experiment, 5 changes were applied during 2 heating and cooling rounds (the PWM duty cycles corresponding to the output voltages were 20%, 40%, 60%, 80%, and 100%), which corresponded to 5 intensity types: very weak (A), weak (B), medium (C), strong (D), and very strong (E). The temperature was applied starting from 29°C and was reset to this temperature after each experiment was completed. The stimulus presentation time was 45 seconds, and subjects were asked to take a break for 30 seconds after each experiment.

In the experiment, the subjects wore the device on their right hands, and the researcher selected one of the five temperature stimuli to present to the subjects’ right hand. The subject responded with temperature sensation level that corresponded to the level he perceived, and the researcher recorded the subject’s responses. The experiment was divided into two rounds according to the temperature change direction. In the first round, the subject’s perception of heating was measured, and the second round was cooling. Each experimental round consisted of results from untrained and trained subjects. The content of the training is that the participants experience different levels several times and were told the intensity level corresponding to the tactile stimulation they felt, and they then participated in the experiment. There were 5 temperature stimuli in each round, and each stimulus was tested 6 times. Each subject was tested 30 times in each round with a random presentation order.

3) STATISTICS

Data were expressed as the mean ± SD, and analysis of variance (ANOVA) was used to test significance of differences when applicable. The difference was statistically significant when P < 0.05.

D. EXPERIMENTAL RESULTS

1) VIBRATION EXPERIMENT RESULTS

The experimental results are shown in Figure 14. The accuracy of the subjects’ identification after training was higher. Regardless of whether the subject was untrained or trained, the accuracy of the intermediate intensity identification was the lowest, while bilateral stimulation identification was higher, which indicates that extreme vibration intensity is easier to identify. Differences between the two sets of data were compared with analysis of variance, and the results are listed in Table 3.

As can be seen from Table 3, for the current level division, training has a significant impact on improving the recognition accuracy (p < 0.05), indicating that the subjects can more accurately distinguish different vibrations after training, so the preset 5 vibration levels were retained and renamed 1, 2, 3, 4 and 5. However, considering that the accuracy rate after training was less than three times the random probability (as the researchers expected), no finer levels were added.

2) TEMPERATURE EXPERIMENT RESULTS

The results of the first round, the heating experiment, is shown in Figure 15. The recognition accuracy of temperature stimulus A is the highest regardless of whether there was training, and the accuracy then decreases sequentially. Finally, the recognition accuracy of temperature stimulus E increases again, indicating that subjects are most sensitive to slow and violent heating but are not as sensitive to intermediate temperatures. Differences between the two sets of data were compared with analysis of variance, and the results were
In Table 4, the heating variance was listed. The distributions of incorrect answers are shown in Table 5.

According to Table 4, training has no significant effect on the recognition accuracy (p > 0.05). In Table 5, when the B level was actually applied to subjects, 60% of the incorrect results believed that they felt level C. And when level C was applied, 52% of the incorrect results believed that they felt level B while 32% thought it was D. When level D was actually applied to subjects, 69% of the incorrect results thought they felt level C while 38% thought it was E. It means that B, C and D were easily confused by subjects. Therefore, cooling modes A, C, and E were retained and renamed I, II, and III. This was done to make sure that the temperature change could be distinguished.

V. HUMAN EXPERIMENTS

According to the result obtained in section IV, we adopted a practical operation to verify the effectiveness of the device. In this section, concentrated sulfuric acid dilution experiment and ammonium nitrate dissolution experiment were selected as examples. These two chemical experiments are typical experiments to explore energy changes. Experiment operation process is shown as Fig 17.

A. PARTICIPANTS AND APPARATUS

Twenty-five right-handed healthy volunteers (10 females, age: 24.52 ± 1.44 years, mean ± SD) participated in the experiments. They had no sensory disorders and had not previously participated in a similar experiment. The experimental procedure was approved by our university ethical committee.
The experimental apparatus included the aforementioned tactile glove and a laptop computer. This apparatus could achieve tactile feedback in accordance with the skin perception characteristics of human hands. The operational scenario is shown in Figure 18.

**FIGURE 18.** Operation scene of a volunteer. (a) operation scene (b) virtual experimental scene adopted in this example (c) the volunteers’ perspective (d) tactile feedback glove device.

### TABLE 8. Heating correspondence.

| $H_2SO_4/ml$ | Real/°C | Device/°C |
|--------------|---------|-----------|
| 0            | 29      | 29        |
| 5            | 63.5    | 39.0      |
| 6            | 67.8    | 41.4      |
| 7            | 73.0    | 43.3      |
| 8            | 76.3    | 44.9      |
| 9            | 80.2    | 46.7      |
| 10           | 83.7    | 47.1      |
| 15           | 96.4    | 46.7      |

B. EXPERIMENT DESIGN AND PROCEDURE

1) EXPERIMENT 1: CONCENTRATED SULFURIC ACID DILUTION VR EXPERIMENT

When concentrated sulfuric acid is diluted, a large amount of heat is released quickly. When 15 ml of 98% sulfuric acid is injected into a large amount of water, the temperature changes are shown in Table 8. In a traditional experimental chemistry teaching process, the concentrated sulfuric acid dilution operation has a high risk and is particularly prone to safety accidents. At present, many school forbid students from actually performing this experiment. Combined with the performance of this device, we choose heating mode IV to simulate the temperature change. For safety reasons, when the device temperature reaches 47°C, it will no longer continue to heat up to avoid burning the skin of the subject. The temperature changes of the device are shown in Table 8, the heating trend is the same, but the absolute value of temperature is different. In addition, vibration mode 2 was used to represent moving the glass rod, and vibration mode 4 was used to represent stirring the glass rod.

Before the start of experiment, the purpose and operation of the concentrated sulfuric acid dilution VR experiment was explained to the subjects. Then, the subjects put on the device and completed the experiment alone. After that, the subjects were asked to complete a questionnaire, and then the data were counted and analyzed by the researchers.

At a room temperature of 29°C, the concentrated sulfuric acid dilution VR experiment scene is opened and connected to Bluetooth. The subject wears the device with both hands to conduct the experiment. By pressing the keyboard, the subject pours concentrated sulfuric acid into a beaker filled with water and stirred the solution with a glass rod.

During the experiment, the subject can visually see the temperature value increasing on the upper computer screen or the device’s OLED screen. At the same time, the platform sends instructions to the device via Bluetooth. The subjects will feel the temperature increase on the back of the hand and will feel vibrations with their fingers. The temperature and vibration changes during the operation will be felt simultaneously.

2) EXPERIMENT 2: AMMONIUM NITRATE DISSOLUTION VR EXPERIMENT

The process of dissolving solid ammonium nitrate in distilled water will absorb heat from environment, and its solubility...
is 190 g. The temperature changes when completely dissolving 30 g of ammonium nitrate in 16 mL of distilled water are shown in Table 9. Combined with the performance of this device, we choose cooling mode II to simulate temperature change, and the temperature changes of the device are shown in Table 9. Both at the experiment and the simulation have the same cooling trend, but the absolute value of temperature is different. In addition, vibration mode 2 is used to represent the operation of moving the glass rod, and vibration mode 4 is used to represent the operation of stirring the glass rod. According to the performance of the actuator, the experimental operation time shall not exceed 60 seconds.

### TABLE 9. Cooling correspondence.

| H2O/ml | Real/°C | Device/°C |
|--------|---------|-----------|
| 0      | 29      | 29        |
| 5      | 24.8    | 24.7      |
| 10     | 20.7    | 21.2      |
| 12     | 19.6    | 19.9      |
| 14     | 18.9    | 19.6      |
| 16     | 18.4    | 19.3      |

Before the start of experiment, the purpose and how to conduct the ammonium nitrate dissolution VR experiment are explained to the subjects. Then, they are asked to wear the device and complete the experiment alone. After that, the subjects are requested to fill out a questionnaire, and then, the data are counted and analyzed by researchers.

At a room temperature of 29°C, the ammonium nitrate dissolution VR experiment scene is opened and connected to Bluetooth. The subject wears the device with both hands to conduct the experiment. The subject slowly pours 16 ml of water into a beaker containing 30 g of solid ammonium nitrate by pressing the keyboard, while stirring continuously with a glass rod.

During the experiment, the subject can visually see a continuous decrease in the temperature on the upper computer screen or the device’s OLED screen. At the same time, the platform sends instructions to the device via Bluetooth. The subjects will feel the temperature decrease on the back of the hand and will feel vibrations with their fingers. The temperature and vibration changes during the operation will be felt simultaneously.

3) USER EVALUATION

In this section, the results of all items except temperature perception are quantified by the scale, with the full score of 10 and the minimum difference of 0.5. Refer to table notes for evaluation details. The subjects’ evaluation results of the authenticity of the system are shown in Table 10.

### TABLE 10. System authenticity.

| Project       | Index       | Result | Positive Ratio |
|---------------|-------------|--------|----------------|
| Authenticity  | Authentic   | 19     | 76%            |
|               | Unauthentic | 6      |                |

In this table, a score of 8-10 was recorded as ‘authentic’. 0-7.9 was recorded as ‘unauthentic’.

### TABLE 11. Vibration and temperature perception.

| Project                  | Index          | Result | Positive Ratio |
|--------------------------|----------------|--------|----------------|
| Vibration Perception     | Suitable       | 22     | 88%            |
|                          | Unsuitable     | 3      |                |
|                          | Heating        | 25     |                |
| Temperature Perception   | Exothermic     | 0      | 100%           |
|                          | Heating        | 3      |                |
|                          | Insentient or Weak | 0  |                |
|                          | Insentient or Weak | 1  |                |

The subjects’ evaluation results of vibration and temperature perception are shown in Table 11.

Vibration evaluation conclusion is the weighted result of two indexes: one index is whether the movement and stirring with the glass rod can be distinguished, and the other index is whether the combination of the vibrations and visual perception is natural, with each having a weight of 0.5.

Volunteers scored the 2 indexes separately. A score of 0 means that they cannot distinguish different vibration sensations at all (or the motion they see is completely inconsistent with the vibration), and a score of 10 means that they can easily distinguish different vibrations (or the motion they see and the vibration match naturally). A scoring results for both indexes of 6 points or greater is considered to be a positive evaluation given by volunteers.

### TABLE 12. Comparison.

| Project                   | Index    | Result | Positive Ratio |
|---------------------------|----------|--------|----------------|
| Compared to Traditional Experiments | Better  | 18     |                |
|                            | Alike    | 4      | 88%            |
|                            | Worse    | 3      |                |
| Compared to a Purely Visual Virtual Experiment | Better  | 23     |                |
|                            | Alike    | 0      | 92%            |
|                            | Worse    | 2      |                |

In this table, a score of 8-10 was recorded as ‘Better’, 5-7.9 was recorded as ‘Alike’, 0-4.9 was recorded as ‘Worse’.

Subjects compared the experimental systems in this article with traditional experiments or purely visual virtual experiments. The evaluation results are shown in Table 12.
In the endothermic experiment, there were individual volunteers who felt a feeling of heat. Excluding personal factors, an analysis concluded that the heat dissipation side of the semiconductor refrigerator could not reach the ideal heat dissipation condition. If the side in contact with the skin (the cold side) is cooled for too long, the heat accumulated by the hot side under limited conditions will transfer to the cold side, resulting in an increase in temperature.

This section selected two typical experiments from a middle-school curriculum to explore energy change and simulated the temperature change caused by endothermic and exothermic reactions in the virtual experimental environment. In the VR experiment, the virtual experiment scene platform presents the experimental operation scene of concentrated sulfuric acid dilution and ammonium nitrate dissolution, while the wearable device enables students’ skin to directly feel the tactile information during the operation. All volunteers said that during the VR experiment, the skin could clearly feel the tactile change, which is interesting and exciting. Compared to real experiments using concentrated sulfuric acid, the subjects thought that the VR experiment was not only novel but also had no fear, and the impressive phenomenon of temperature change inspired them to think about the scientific principle behind the experiment.

The statistical results of the questionnaire survey show that the concentrated sulfuric acid dilution and ammonium nitrate dissolution VR experiment designed in this article are better than traditional methods in terms of science, safety, authenticity and interactivity.

VI. DISCUSSION
According to the statistical data in Table 10-12, this device basically meets the experimental requirements in terms of authenticity and vibration and temperature perception. Therefore, this device can be used as an extension of traditional VR technology to achieve tactile feedback during human-computer interaction. In addition, we asked the volunteers to propose optimization suggestions according to their own experience, and 17 volunteers (68%) provided feedback on improvement measures, as shown in Figure 19.

Eight volunteers thought that the upper computer experimental scene needed to be improved, including the simple animation and fewer available experiments. Two of the volunteers believed that there was a mismatch between the visual and tactile information during the experimental operation, that is, the movement of the virtual object they saw and the sensation they felt were not synchronized in time. After excluding individual differences, researchers believe that there are two reasons for this issue. One is the processing performance of the upper computer. Complex virtual scenes require a high-performance processor, and using low-performance processors will cause lag or frames to drop. The second issue is related to communication delay, including the data transmission time and program processing time. After testing, the delay time of the device was within 0.2 s, and 92% of the volunteers stated that they did not sense an obvious dislocation between the vision and tactile sensations, and research to shorten the delay time will be addressed in further work.

In view of the various distributions of haptic corpuscles in different positions in the skin, the same tactile stimulation will produce different sensations in different positions. In this article, combined with real experimental operations, 12 actuators are distributed on the fingertips and the back of the hand. Two volunteers believed that the distribution position of the actuators affected the authenticity of the tactile information. The analysis shows that the sensation produced by different experimental operations are different, and the installation position of the actuator should be optimized according to a large number of experimental statistics.

Five volunteers believed that the current device did not fully reproduce other tactile information during the experimental operation. For example, friction is very important to distinguish a material and the weight of the object when grabbing an object. The volunteers felt that the absence of this aspect affected the authenticity of the experimental operation. Considering the size and flexibility of the device, we believe that a variety of tactile information should be selected to achieve a more natural human-computer interaction. Therefore, the device selected the two most important tactile changes in the experimental process to feed back to the user while considering both the volume and performance of the device.

Six volunteers believed that the current interactive methods had an impact on the authenticity of the operation, and the most important aspect was the failure to reflect wrong operations during the experiment. At present, the keyboard interactive method can complete normal experimental operations, and gestures and voice interaction can be regarded as a key direction of future research.

Considering the hysteresis of temperature control, the actuator with small inertia is needed to achieve high frequency
temperature alternation (just similar to the figure 20, period is T). According to the conclusion in Section III, the semiconductor refrigerator mentioned cannot achieve rapid change in cooling and heating. The selection of new components can be researched in future works.

VII. CONCLUSION

The tactile glove designed in this article, which was based on the skin temperature and vibration perception characteristics of the human hand, achieved multiple tactile feedback according to the skin perception characteristics of the action area, improved the authenticity and immersion in the human-computer interaction process, and further extended traditional human-computer interaction methods. The proposed device includes 12 small actuators, which integrate functions such as tactile change, temperature acquisition and display. Through perception experiments, this device was shown to achieve multiple tactile feedback. According to the recognition accuracy, the levels of vibration (1-5), heating (1-IV), and cooling (I-III) are determined. This device overcomes the shortcomings of actuators with a simple action mode, which are used in traditional tactile feedback research and do not conform to skin perception characteristics. Combining experience with the virtual experimental teaching scene, this device achieved satisfactory results. Specifically, 76% of the volunteers had positive comments about the authenticity of the device, and more than 80% of the volunteers noted that the device’s tactile changes were appropriate. Compared to a virtual experiment without tactile information, 92% of the volunteers believed that this device with tactile feedback made the experimental operation more authentic.

This article presented a small device that can achieve vibration and temperature feedback, which conform to the perception characteristics of hand skin. The device is low cost and has high performance and can be used as tactile experience equipment for VR technology. Based on traditional audio-visual experiences, this device adds tactile information to promote the integration of multiple senses. This device will play an important role in virtual game, virtual medical operations, virtual training and in other fields.

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