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RESEARCH ARTICLE

XR CUBE: Multi-Sensory Intelligent Interaction Device for Extended Reality Application

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ABSTRACT In recent years, the integration of XR technology into everyday life has marked a new era. As these technologies advance and innovative design concepts are introduced, the user's interactive experience is continually enhanced. To enhance immersion in virtual worlds, based on the existing virtual-physical model (VPModel) platform, we have introduced multi-sensory modules to XR using the modular design approach, allowing users to choose different sensory modules according to their needs. This approach will provide users with a more comprehensive interactive experience through multi-channel cues. Contrasting with the prevalent use of somatosensory suits in wearable technology, we have selected three commonly used sensors and perceptual stimuli to develop integrated, wearable multi-sensory modules. Subsequently, we employed the modular design approach to iterate our sensory devices, resulting in eight modular multi-sensory components. These components comprise input devices for "user behavioral data acquisition based on multi-sensor", and output devices for "multi-sensory feedback based on somatosensory simulation devices". This study invited 10 users to conduct product trials on these two generations of devices. Through the analysis of the collected data and user feedback, we finally created the XR sensory device kit that integrates multi-sensory, wearable, modular, and intelligent - "XR CUBE."

INDEX TERMS Extended reality, human-computer interaction, integrated design, modular construction, product design.

I. INTRODUCTION

Wearables and extended reality (XR) devices introduce new interaction paradigms with their unique function forms. As application scenarios diversify, people have new requirements for intelligent interactive devices: more immersive XR experiences, more convenient ways to use the devices, and more personalized device customization solutions. To realize the multimodal intelligent interaction for XR devices, we attempted to build an XR sensory device that combines multimodality, wearability, modularity, and intelligence.

First, previous work explored the role of multi-sensory technologies in increasing the immersion of XR experiences, through experimental studies such as visual, acoustic, haptic [1], [2], heat and odor feedback [3]. These studies evaluated the dimensions of emotion, cognition, and arousal and showed that multi-sensory XR experiences can increase the audience's sense of immersion in virtual environments, which in turn affects the user's emotional and cognitive appraisal, suggesting the importance of multimodal feedback for immersive interactions in XR environments [4], [5]. Meanwhile, the Internet of Senses (IoS) has been receiving significant attention from researchers and telecom vendors recently. Sehad et al. introduced a real-life testbed Unmanned Aerial Vehicle (UAV) based system that leverages different technologies, including VR, 360° video streaming, and edge computing with haptic feedback for reliable immersive teleoperation in scenarios [6], [7]. In this paper, based on the existing research foundation of VPModel platform [8], we tried to use XR technology and multimodal

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human-computer interaction to enhance the immersive experience of users. Adding multi-sensory to XR creates a sense of immersion that couldn't be brought by using a single perception in traditional XR.

Secondly, to enhance the XR experience through multi-sensory technology, researchers have developed haptic gloves such as Dexmo, HaptX, TactGlove, SenseGlove Nova, somatosensory suits such as exoskin, Tesla Suit, e-skin, and a series of virtual environment devices such as Lead Skin and ElecSuit based on Electrical Muscle Stimulation (EMS). Unlike the common tactile garments in the current market, we used modular design thinking to set up each sensory module as an independent unit and employed freely combinable encapsulated boxes to contain the components of the sensory modules.

Thirdly, with the development of artificial intelligence technology, some studies have implemented gesture recognition [9], natural language recognition [10], AI segmentation technology [11] and other techniques based on machine learning [12], biosignals, and other methods to achieve a more diverse and realistic interaction experience in XR environments. Ratcliffe et al. [13] summarized the results of 30 surveys from 46 XR researchers, and then determined the portability and reproducibility of leveraging XR devices' built-in data collection capabilities (e.g., hand, gaze tracking). He suggested conceptualizing XR technology as an interactive technology and a powerful data collection device. In this paper, we used machine learning algorithms to process the collected user physiological data to create intelligent sensory modules in XR environments, realize user hand action recognition in XR environments and create intelligent human-computer interaction (HCI) between the user and XR environments.

Finally, the modular product design (MPD) method is a very classic and important method for product personalization with the advantages of diversity, rich combinations and detachability, and is widely used in product design [14], [15], [16]. Pandremenos and Chryssolouris [17] explored the MPD architecture and its ability to enable simple and rapid product customization to meet individual user needs. We combined the various sensory modules into a set of "XR CUBE". Different users can customize the combination of different modules according to the specific use scenarios to achieve personalized customization and satisfy the user's multi-scenario needs.

The XR CUBE device kit was optimized in two iterations. In the first generation of device development, we selected three common sensors and sensory stimuli, such as posture sensor, heart rate sensor, and vibration sensation, to create an integrated "wearable multi-sensory integration module". To improve the usability of the product, we invited 10 volunteers to participate in the usability testing of the first-generation device. According to the user's feedback and the collected data, the first integrated device was optimized modularly and iteratively. In the second generation of device development, four of the most representative and widely used sensors and four of the most universal and critical sensory stimuli were selected by analyzing and comparing the characteristics of various XR scenarios. The sensory modules were embedded into the same size hexagonal boxes, and through the free combination of different modules to realize the personalization of wearable devices. As before, we invited 10 users to participate in the second-generation device again. The overall feedback was that the second-generation device was more user-friendly and better looking than the first generation.

In this study, we introduce novel multi-sensory modules, called extended reality cube (XR CUBE), which adopts the modular design concept. The implementation of the XR CUBE system requires overcoming challenges such as communication between sensory modules and XR devices, user behavioral data acquisition based on multiple sensors, multi-sensory feedback based on somatosensory simulation devices, modular and wearable design of the device. XR CUBE not only perfectly realized the creation of high immersion and personalized customization during user use, but also realized the advanced design from experimental level research to user-oriented product level.

The remainder of this paper is organized as follows. Section II describes the system of XR CUBE, and then develops in detail the development process of its eight sensory modules. Section III presents the structure design process of XR CUBE, which also includes user feedback from the old and new generations of the product. Section IV shows the practical application scenarios of XR CUBE with examples. Finally, Section V concludes the paper and discusses the current limitations and development prospects of the product.

II. XR CUBE SYSTEM DESCRIPTION

To enrich the traditional XR experience with a broader range of sensory experiences beyond hearing and vision, we deployed the sensory module–XR CUBE. The sensory module consists of input devices "user behavioral data acquisition based on multi-sensor" and output devices "multi-sensory feedback based on somatosensory simulation devices" (Figure 1). XR CUBE achieves the intelligent HCI in MR environment and enhances the user's sense of experience through the acquisition, processing, and analysis of multi-modal physiological or physical signals by the sensors. Data collection serves dual purposes: acquiring physiological data for XR environments and triggering intelligent interactions between virtual scenes and somatosensory devices. The sensor data processing mechanism in XR CUBE can be divided into the following three categories: (1) The development board processes the data collected by the sensors and outputs it directly to the somatosensory simulation device; (2) The onboard hardware neural network of the development board processes sensor data through corresponding algorithms and outputs the processing results to HoloLens; (3) Sensor data is transmitted to HoloLens, where its control unit processes the data algorithmically for corresponding actions. Sensory feedback is achieved by the XR CUBE control unit sending control signals based on processed user data, controlling the somatosensory simulation components for feedback. This feedback primarily simulates physical sensory experiences corresponding to the MR scene. The somatosensory simulation device's execution mechanism is twofold: (1) It directly executes commands based on the development board's processed sensor data; (2) It receives and executes commands from HoloLens.

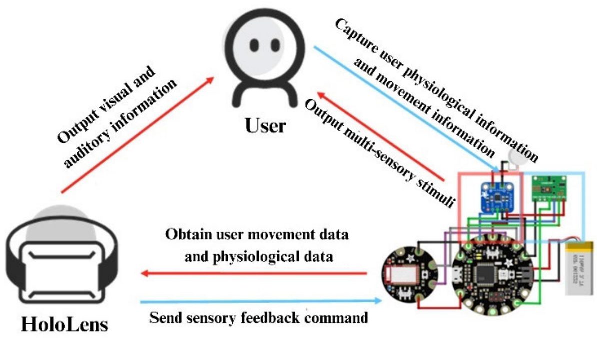

FIGURE 1. Multimodal HCI based on sensory module.

A. SYSTEM OVERVIEW

The sensory module connects various sensors, components, Bluetooth modules, lithium batteries and other hardware devices to the Arduino development board, forming a closed-loop control system. This system is designed for efficient collection of user physiological data, enabling Bluetooth communication between Arduino and HoloLens, and facilitating interaction with the user's physical perception. We selected three commonly used sensors and sensory stimuli: posture sensor, heart rate sensor and vibration sensation to create the multi-sensory integrated module. The hardware circuit design is shown in Figure 2. Considering the project requirements comprehensively, we selected the Genuino 101 development board as the development platform. It has different functional modules, and each module has its own characteristics and powerful functions, which provide great support for the development of sensory modules. At the same time, to meet the voltage requirements of the development board, we selected a boostable and rechargeable lithium battery (BH903462) to power the development board and all peripherals. It not only provides ample power for frequent use, but also has the advantages of charging and discharging protection and compact size, which can help to improve the safety, convenience, and comfort of the wearable device.

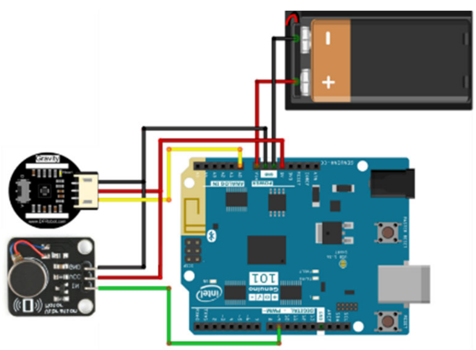

FIGURE 2. Hardware circuit design for multi-sensory integrated module.

In this study, HoloLens serves as a standalone holographic device, functioning as the central mechanism. It reads sensor information from the Arduino board and commands the simulation devices within it. Arduino and HoloLens transmit information via Bluetooth Low Energy (BLE). BLE has extremely low operating and standby power consumption, which is suitable for audio data transmission without large streams and high real-time requirements of sensory modules. In this project, BLE provided by Genuino 101 is used as the Bluetooth communication module to realize the hardware and software wireless communication for data transmission and reception of the sensory module (Figure. 3). HoloLens can read user physiological or physical signal data captured by the sensors, including posture, heart rate, pressure, gesture and other data information. Then, the somatosensory simulation device can obtain HoloLens commands, including vibration frequency, pressure level, pulse current intensity, temperature and other commands. The above data are stored in Bluetooth characteristics. To exchange characteristics between the two devices and realize data transmission, the corresponding Bluetooth modules need to be written separately. The sensory module defines a service for these communications, which contains four characteristics to transfer information such as heart rate, hand action accelerometer data, hand action categorization output by the model, vibration information, etc. Arduino and HoloLens transfer the information by reading or writing the Characteristic's internal data to pass the information.

FIGURE 3. Send and receive Bluetooth messages.

The technical implementation is completed by programming in Arduino and Unity, and using the corresponding libraries to complete the functions of acquiring sensor data and setting up Bluetooth services in the Arduino program. In addition to the traditional compilation toolchain, Arduino provides a processing-based integrated development environment that is compatible with the Arduino programming language. The corresponding Arduino program is burned into the Genuino 101 circuit board to realize the development of the Arduino program. Secondly, since the Arduino can only be serialized, the data from the three sensors can only be acquired sequentially. After many tests, we finally decided to collect heart rate sensor data every 0.81 seconds, inertial measurement unit (IMU) data every 0.85 seconds, and gesture

TABLE 1. Results of the usability evaluation of the sensory module.

Primary Indicator	Necessity		Effectiveness		Ease of use	
Secondary Indicators	***Usage rate***	***Influence***	***Realism***	***Enjoyment***	***Development difficulty***	***Operability***
Posture sensor	high	high	high	high	medium	high
Pressure sensor	medium	medium	high	medium	low	high
Heart rate sensor	high	medium	high	low	low	high
Myoelectric sensor	low	high	low	high	high	medium
Vibration sensation	High	High	High	High	Low	High
Acupressure sensation	High	Medium	Low	Medium	High	Medium
Pain sensation	High	High	High	Medium	Low	High
Thermal touch sensation	High	High	Medium	High	Low	High

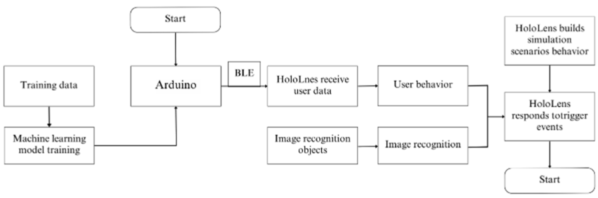

FIGURE 4. Sensory module technical framework diagram.

recognition results every 4 seconds. This can better achieve the functional goals of collecting and regularly updating the user's upper limb movement and heart rate information, as well as transmitting vibration information (Figure 4).

B. SENSORY MODULE

For selecting sensory modules in XR CUBE, we referenced the product usability cognitive system proposed by Hartson [18], and established the function selection of sensory modules based on the quality function deployment (QFD) method [19] according to the characteristics of the XR platform. The sensors and somatosensory simulation devices required for the XR CUBE are considered in terms of three dimensions (Level 1 indicators): necessity, effectiveness, and ease of use. Necessity is evaluated in terms of usage rate and influence (Level 2 indicators), effectiveness is evaluated in terms of realism and enjoyment of the sensory simulation (Level 2 indicators), and ease of use is evaluated in terms of development difficulty and operability (Level 2 indicators).

In developing the XR CUBE's sensory module, we utilized a function selection evaluation index, involving five expert researchers in our lab to analyze and compare XR application scenarios. Finally, four representative and universal sensors and sensory stimuli were selected for in-depth research and applied to the development of XR CUBE sensory module. The four sensors selected are: ''posture sensor'' for monitoring the user's motion data and human action recognition during scene interaction, ''pressure sensor'' for fit pressure measurement evaluation, ''heart rate sensor'' for user health monitoring, and ''electromyography (EMG) sensor'' for motion intent recognition. The four sensory stimulations achieve somatosensory simulation effects through the combination of corresponding functional devices, namely: ''vibration sensation'' through the vibration motor to simulate the corresponding functions of the scene interaction, ''acupressure sensation'' through the motor-driven mechanical structure design to simulate the weight and reaction force, the ''pain sensation'' simulating muscle soreness through the low-frequency electric pulse muscle stimulation module, and the ''thermal touch sensation'' simulating the heat generation phenomenon through the heating up of the flexible heating pad. The researchers made a reasonable assessment of the usability of these eight sensory modules in the XR CUBE, which were classified as high, medium, and low [20], and the assessment results are shown in Table 1. In the actual application process, users can choose the appropriate sensory modules according to the functional and perceptual simulation needs of different XR scenarios. In the following, we took a typical application scenario of XR in the healthcare field, upper limb rehabilitation training, as an example, including desktop grasping, wall groping, ball throwing and cargo lifting scenarios. The following is a detailed introduction to the development, selection and algorithm construction of XR CUBE eight sensory modules.

1) POSTURE SENSOR

XR scene interactions often need to recognize user hand actions to make virtual objects interact accordingly. Since there are fewer types of hand action recognition in HoloLens and the field of vision is narrow. The range of user actions in the wearable device simulation scene is large, and some actions will appear outside the detection range of the HoloLens camera. Visual recognition cannot be used to identify user actions. To mitigate the issue of limited field of vision in XR applications, the posture sensor is employed to gather the user's action data. This data, processed through a motion pattern recognition algorithm, helps ascertain the user's posture. By interpreting the user's actions via the posture sensor, the virtual scene dynamically adjusts in response to user behavior. This interaction fosters a more natural, straightforward, and convenient HCI method, thereby enhancing the overall XR experience.

To accurately obtain the object's posture, it is necessary to obtain its acceleration and angular velocity in three-dimensional space, enabling precise displacement projection. This part of the data can be obtained through the accelerometer and gyroscope on the IMU. The Genuino 101 development board has integrated IMU sensors and hardware engine pattern matching engine (PME). The built-in accelerometer and gyroscope can simultaneously acquire acceleration and tilt data. Furthermore, the PME is used to classify and recognize user actions, so user action recognition can be achieved without adding peripherals, which plays a role in reducing the size of the sensory module.

After completing the preparation of the attitude sensor, we took the throwing action in upper limb rehabilitation training as the task to identify the user's hand actions in the ball throwing scenario. Therefore, four hand actions need to be categorized: rising, throwing, falling, and stationary. Since hand actions are made at any time, the system needs to recognize the classification of hand actions continuously. Currently the time interval for recognition is set to 3 seconds, i.e., all hand actions are classified within 3 seconds. To find out the combination of algorithms with the highest accuracy, the accuracy of different algorithms and data sources for recognizing user actions needs to be tested. The development of hand action recognition involves three steps: collecting hand action data, training and saving the machine learning model, and utilizing the model for predictions.

To train the model, four hand action data are first required. The X,Y,Z axis data was collected from the accelerometer and gyroscope on the Arduino board. The Arduino board needs to be fixed on top of the wrist during data acquisition to ensure that it is in the same position as the real wearer. To get higher accuracy in real time recognition, when collecting the data, the movements collected when making the same hand movement will be slightly different. A part (about 50%) of the hand movement data covers hand movements from beginning to end, while the other part only takes the first half or second half of these movements. This methodology caters to real-time detection scenarios where a 3-second motion capture might not represent a full hand movement, hence the partial data collection strategy. A button on the Arduino board controls the data collection process. After the data are collected, they are downsampled, thus converting data of different time lengths into sample data of the same size. All the data will be saved in the Flash of the Arduino board to facilitate the training and prediction needs of the algorithm.

To run the action recognition algorithm directly on Arduino, we have chosen the radial basis function (RBF) and k-nearest neighbor (KNN) algorithms, which do not require complex dependencies and runtime environments. Both algorithms were trained directly on Arduino and the trained models were saved in Flash. We compared their accuracy in hand action recognition.

The RBF radial basis algorithm was proposed by Powell in 1985 [21]. A radial basis function is a real-valued function whose value depends only on the distance from the origin, i.e., $\Phi(x) = \Phi(\|x\|)$, or it can also be the distance to any point c, which is called the centroid, i.e., $\Phi(x, c) = \Phi(\|x - c\|)$. RBF neural network is a three-layered neural network including input, hidden, and output layer. The transformation from the input layer to the hidden layer is nonlinear, while the transformation from the hidden layer to the output layer is linear. The basic idea of RBF is to use RBF as the "base" of the hidden unit to form the hidden layer space, so that the input vector can be directly mapped to the hidden space without the need to connect through the weights. When the center point of RBF is determined, this mapping relationship is also determined. Among other things, the role of the hidden layer is to map the vectors from low dimensions to high dimensions, so that the case of linear indivisibility in low dimensions can become linearly divisible in high dimensions. In this way, the mapping of the network from inputs to outputs is nonlinear, while the network outputs are linear with respect to the adjustable parameters. The network's weights are directly solvable from linear equations, enhancing learning speed and avoiding local minima issues.

The activation function of the RBF algorithm can be expressed as:

$$R\left(x_p - c_i\right) = exp\left(-\frac{1}{2\sigma^2}\left\|x_p - c_i\right\|^2\right) \tag{1}$$

where the structure of x_p radial basis neural network can be obtained as the output of the network:

$$y_i = \sum_{i=1}^{h} w_{ij} exp\left(-\frac{1}{2\sigma^2}\left\|x_p - c_i\right\|^2\right) j = 1, 2, \cdots, n \tag{2}$$

A least squares loss function representation is used:

$$\sigma = \frac{1}{P}\sum_{j}^{m}\left\|d_j - y_j c_i\right\|^2 \tag{3}$$

The KNN algorithm is the basic machine learning algorithm. For an input vector x that needs to be predicted, the algorithm finds the set of k nearest vectors to vector x in the training data set, and then predicts the class of x as the one with the highest number of classes among these k samples. The KNN algorithm is executed as follows: find the k samples closest to x in the training set T according to the distance measure algorithm, and notate the set denoted by these k sample points as N_k(x). The distance measure algorithm used here is Euclidean distance. For two points $x(x_1, x_2 \ldots, x_n)$ and $y(y_1, y_2 \ldots, y_n)$ in an n-dimensional space, the Euclidean distance between x and y can be expressed as:

$$d_{xy} = \sqrt{\sum_{k=1}^{n}\left(x_k - y_k\right)^2} \tag{4}$$

Determine the category y to which instance x belongs based on majority voting:

$$\mathrm{y} = \mathrm{argmax}\sum_{\mathrm{x_i} \in \mathrm{N_{k(x)}}} \mathrm{I}\left(\mathrm{y_i}, \mathrm{c_j}\right), \mathrm{i} = 1, 2, \ldots, \mathrm{N}; \quad \mathrm{j} = 1, 2, \ldots, \mathrm{K} \tag{5}$$

$$I(x, y) = \begin{cases} 1, & if\ x = y \\ 0, & if\ x \neq y \end{cases} \tag{6}$$

To compare the accuracy of the two machine learning algorithms for action recognition, accelerometer data is used to test the classification accuracy of the RBF and KNN algorithms. To prevent the data drift of the six-axis accelerometer, the accelerometer was calibrated first during the training data entry. Then the accelerometer data of IMU was used to train the algorithm. The RBF and KNN algorithms were successively trained with the IMU data, and some sample data were collected for offline testing of the training effect. The results are shown in Table 2. The test results show that the difference between RBF and KNN in classifying hand actions is small. The RBF algorithm with a slightly higher correct rate is finally selected as the algorithm for classifying hand actions.

TABLE 2. Classification accuracy of RBF and KNN algorithm.

Classification Algorithm	Sample Size	Identify the Correct Number of Samples	Recognition Accuracy
RBF algorithm	400	314	78.5%
KNN algorithm	400	297	74.3%

Since the collected data is divided into two kinds of data, accelerometer and gyroscope, this study explores whether the accuracy of the algorithm can be further improved by a voting strategy [22]. The voting strategy refers to the algorithm voting the data recognition results of the two sensors separately. First, the models were trained with these two kinds of data separately and saved. For prediction, the classification results of these two models are voted. Only when both models detect that the hand has made a corresponding action will the classification result of this action be output. We experimentally compared the recognition accuracy of yes/no voting strategies, i.e., without voting strategy: using accelerometer and gyroscope respectively; with voting strategy: using both sensors simultaneously. In the experiment, whether the algorithm recognized correctly or not was determined by comparing the subject's arm actions with the classification results of the actions displayed on the HoloLens screen, with a total number of 400 samples. The test results are shown in Table 3. Ultimately, due to the accelerometer's higher accuracy and the need for real-time recognition, the voting strategy was not adopted, favoring accelerometer data for action classification.

The RBF algorithm was deployed on an Arduino board and tested for its real-time classification effectiveness. In the actual application of the project, there is a situation that the user did not complete a complete throwing action during the fetch cycle, which leads to a decrease in the correct rate of throwing action recognition compared to the test. The results are shown in Table 4.

TABLE 3. Accuracy of Yes/No adoption of voting strategies.

Arm Actions	No Voting Strategy		Adoption of Voting Strategies
	Accelerometers	*Gyros*	*Accelerometers and gyroscopes*
Throw	72.5%	66%	67.8%
Up	70.2%	69.8%	67%
Down	68.8%	65%	72%
Rest	74.8%	70.5%	73.3%

TABLE 4. Correctness of throwing motion recognition in real-world applications.

Number of Tests	Number of Correct Identifications	Correct Rate
400	289	72.3%

We experimentally tested the probability that the system could count correctly after the user made the correct operation. ach action was repeated 400 times. The specific actions tested included: grasping an object in a grasping scenario, touching an object in a touch-height scenario, throwing a ball into a basket in a throwing scenario, and placing goods in a designated location in a loading and unloading scenario. The test results are shown in Table 5.

2) PRESSURE SENSOR

The sensor will undergo micro-deformation when under pressure, so that it can detect the contact pressure and weight data between the external stimulus and the pressed subject. The pressure comfort zone for the normal condition is 1.96–3.92 kPa (14.7–29.4 mmHg), and the pressure threshold of discomfort to be around 5.88–9.80 kPa (44.1–73.5 mmHg), but it depends on the individual condition of the treated body part and body position [23]. When the pressure value is higher than 1.96 kPa, there is a negative correlation between the pressure value and the comfort level, too high of a pressure will make people feel uncomfortable, cause numbness to the body part, or even cause breathing difficulty and other serious damage to health [24]. Design evaluation tests commonly use it to judge the comfort level of wearable devices [25].

In XR upper limb rehabilitation, the fit of the exoskeleton to the body is evaluated by measuring the pressure between the user and the device. Dynamic force measurements are obtained through thin-film pressure sensors whose resistance changes with applied force. Ultra-sensitive pressure measurement can be realized by combining the sensor with a static resistor that converts the force of contact by dividing the pressure. The FlexiForce thin-film pressure sensor, chosen for its softness, flexibility, and low power consumption, is ideal for embedding in compact spaces like the XR CUBE and is used to detect force levels between the exoskeleton and the user (Figure 5).

In terms of pressure data acquisition, the Arduino development board acquires the pressure sensor data through analog-to-digital conversion. It processes the acquired information by calling the anologRead() function, transforming the acquired analog signal into a digital signal (waveform). The sampling time is set at 100ms, considering the system requirements and the board's capabilities. The continuous pressure value obtained offers insights into the relative force exerted between the user and the equipment, aiding in subsequent evaluations.

TABLE 5. Accuracy of motion counting.

	Grab	Balls Go in the Basket	Touch Objects	Successful Loading	Successful Unloading
Correct Rate	100%	100%	100%	100%	100%

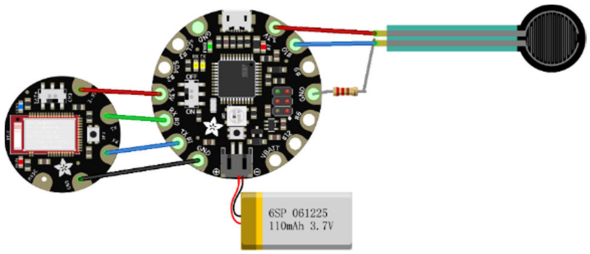

FIGURE 5. Pressure sensor modules.

3) HEART RATE SENSOR

By monitoring heart rate, it can track and record the user's heart rate data over time, which can reflect the user's health status, emotional state, exercise intensity, exercise training mode, etc. In XR upper limb rehabilitation training, heart rate monitoring can be used to display the user's heart rate data in real time, simulating the heart rate monitoring function of a wearable health device. The chosen MAX30102 heart rate sensor aligns well with XR CUBE's requirements due to its quick response, low power consumption, stable performance, and environmental adaptability (Figure 6).

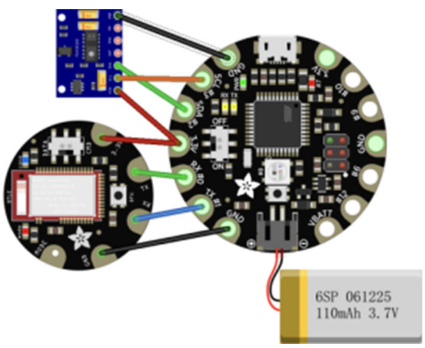

FIGURE 6. MAX30102 Heart rate oximeter sensor.

For heart rate data acquisition, initial calibration is necessary, followed by a waiting period for data recording. To ensure signal accuracy and minimize noise and myoelectric interference, circuit conditioning precedes pulse feature extraction. Considering the computational complexity and real-time performance, the moving average filtering method is selected to filter the pulse signal. Then the heart rate is calculated based on the average number of samples between each neighboring crest of the reflected light signal from the infrared light source during k cycles.

4) SEMG SENSOR

The bioelectrical signals accompanying muscle contraction can reflect the functional status of human muscles and nerves such as the degree of excitement, fatigue, and conduction speed of muscle activity. Analyzing EMG signals to recognize characteristic human behaviors enables interactive controls like action recognition, gesture control, EMG prosthetics, and intelligent exoskeletons [26]. DFROBOT sensor has the advantages of precision, miniature, easy to use, portable, wireless, with data storage function, etc., which is suitable for integrating into wearable devices. It is more in line with the functional requirements of the XR CUBE, as shown in Figure 7.

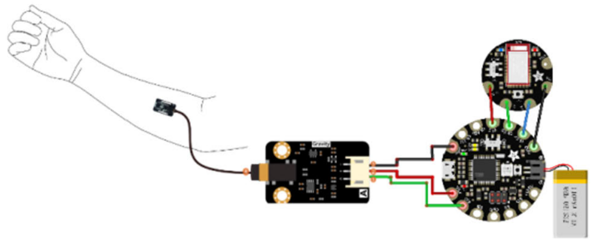

FIGURE 7. sEMG sensor module.

In surface electromyography (sEMG) data acquisition, the sEMG signal needs to be calibrated by the user before measurement. During calibration, it is necessary to relax the muscles on the arm and calm the body and mind, while recording the maximum value indicated by the serial monitor as the reference signal. Connect the filter amplification circuit of the dry electrode sEMG sensor to the analog input interface of the development board. The weak human body sEMG signal within the range of $\pm$1.5mV is amplified 1000 times through the filter amplification circuit. The noise (especially power-line interference) is effectively suppressed through differential input and analog filter circuit. After importing the official EMGFilters library file and setting the calibrated reference value, the output signal of the sEMG sensor can be observed and recorded.

5) VIBRATION SENSATION

Vibration sensation uses mechanical vibration as specific feedback to enhance the immersive experience of XR. It can modulate parameters such as amplitude, frequency, pulse duration and task cycle to deliver different reminder messages to the user. In XR upper limb rehabilitation training, the vibration feedback is given to the user through the vibration simulation device. It can simulate the vibration function of the upper limb exoskeleton device, presenting a higher-fidelity product prototype and a more realistic usage process, such as simulating the startup and assist of the exoskeleton. It also creates more immersive simulation scenarios, like mimicking the sensation of a ball dropping to the ground.

The XR CUBE's vibration module Is implemented using an Adafruit Flora to control the DRV2605L haptic motor drive and flat vibration motor, as shown in Figure 8. The

DRV260x series devices use a special linear resonant actuator (LRA) control algorithm called automatic tracking. Automatic resonance has many benefits and makes LRA integration simple: stronger, more consistent actuator vibration; overdrive and LRA braking capabilities, better response time.

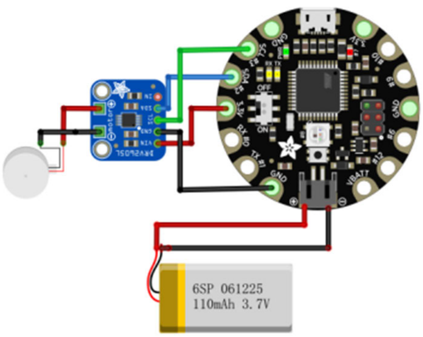

FIGURE 8. Vibration sensation module.

In terms of control strategy and implementation method, before using the flora development board, it needs to import the corresponding library in Adafruit, then search for DRV2605 in the management library and install the library of haptic driver, and through the mode selector function to select multiple different vibration modes. After connecting the components, considering the needs of XR upper limb rehabilitation training scenario simulation, set different trigger conditions, and write the universal windows platform application then store them to HoloLens. HoloLens can judge whether the trigger conditions are met according to the sensor data and the object changes in the virtual scene. When it detects that the conditions are met, HoloLens sends vibration amplitude commands to the Arduino board. Using the DRV2605L amplified driver, it can be controlled directly through the digital pin of the Arduino, and the vibration intensity of the motor can be controlled through pulse width modulation. Thus, the process conveniently converts electrical signals into mechanical vibrations, activating the vibration motor. The vibration motor starts, allowing the user to feel vibration feedback of different intensity, including interval vibration, gentle vibration, medium-high strength vibration, and gradual strength and weakness modes.

6) ACUPRESSURE SENSATION

Acupressure sensation uses mechanosensory feedback to give users force feedback, which can provide haptic feedback by squeezing or stretching the skin [27]. In XR upper limb rehabilitation training, acupressure sensation can simulate the pressing and assisting functions of exoskeleton, as well as the force feedback caused by the weight of physical objects in XR scene. The XR CUBE platform chooses a motor-driven approach to achieve the mechanosensory feedback, and integrates it with a smart structure into a wearable module to simulate the feeling of tapping and pressing.

The XR CUBE pressure perceptual module is achieved using an Adafruit Flora mini servo controller, as shown in Figure 9. Considering the wearable comfort, we chose a small-sized mini servo combined with a linkage structure to give the wearer pressure in the vertical direction from the bottom of the module. Since the pressure feedback device needs to be activated by the data of pressure sensor when simulating the physical weight. Therefore, the two modules of acupressure sensation sensing and the pressure sensor are often bound together.

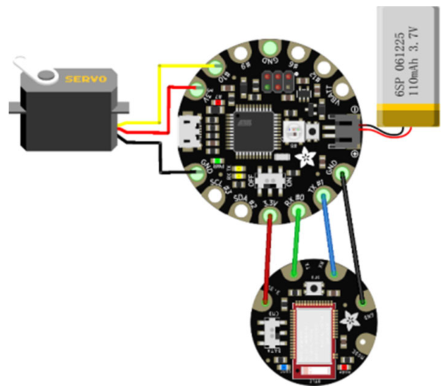

FIGURE 9. Acupressure sensation module.

In terms of control strategy and realization method, it is necessary to write corresponding pressure modes in the XR CUBE device according to different events: (1) When the set pressure condition range is reached, HoloLens sends the corresponding mode command to the Flora development board through the Bluetooth module, calls the vibration amplitude setting function corresponding to the preset pressure condition to accept the command, and feeds back the corresponding tactile sensation to the user; (2) In conjunction with HoloLens settings, a collision detection algorithm monitors user interactions in the virtual scene. It then signals the control board to activate the mechanical device, providing vertical thrust to the user. During the development of the project, we designed the acupressure perceptual simulation device based on the mechanical structure as shown in Figure 10.

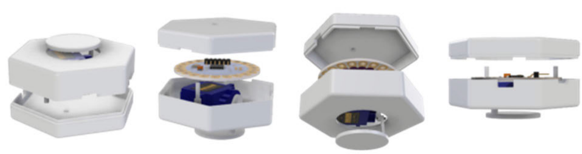

FIGURE 10. Acupressure sensation simulation device based on mechanical structure design.

7) PAIN SENSATION

Pain perception is generated by electrical stimulation feedback, which arouses cutaneous perception by local electrical stimulation of sensory afferent nerve endings. In XR upper limb rehabilitation training, users are given weak current pulse stimulation through a pain simulation device, which can simulate the user's muscle soreness in the simulation scene. The transcutaneous electrical nerve stimulation (TENS) pulse muscle electrical stimulation device selected by XR CUBE uses low-frequency pulses to interfere with nerves. By adjusting the pulse frequency, the intensity of stimulation can be controlled, bringing a more realistic sense of immersion, as shown in Figure 15. It is a packaged product. The size of the patch is 2.5×2.5cm, the size of the main device (controller and battery) is 4 × 4cm. The interfaces are: ① power switch; ② lithium battery interface; ③ Micro USB charging interface; ④ muscle detection indicator light (after turning on the machine, the indicator light goes out; after setting the stimulation level, the indicator light stays on); ⑤ low-battery indicator; ⑥ silica gel electrode interface; ⑦ Bluetooth 4.0 module (Figure 11).

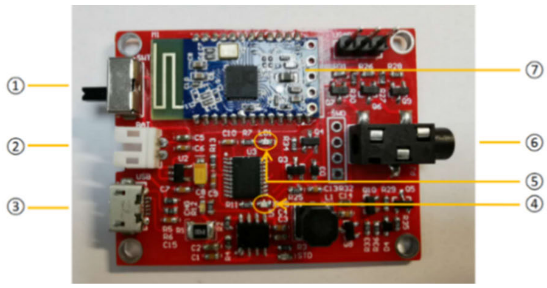

FIGURE 11. Pain sensation module.

In terms of control strategy and implementation method, we need to write different events in XR CUBE, as well as the corresponding pulse current patterns. When the trigger condition is reached, HoloLens sends the corresponding pain mode command to the TENS pulsed muscle electrical stimulation device to realize the pain perceptual feedback.

8) THERMAL TOUCH SENSATION

Thermal touch sensing transmits sensory signals to users through changes in temperature. In XR upper limb rehabilitation training, users are given heating stimulation through thermal touch simulation devices, which can simulate the effect of heating in virtual scenes, such as being close to a fire in a firefighting operation scene, and represent the working hours of wearable devices. The PET film heating sheet offers a safe and reliable temperature range, good flexibility suitable for various unique and uneven surfaces, and low energy consumption. It is commonly used in home physiotherapy devices, making it well-suited for XR CUBE's functional requirements. The thermal touch module is realized by using Adafruit Flora to control the PET film heating pad, as shown in Figure 12.

In terms of control strategy and implementation method, XR CUBE needs to program corresponding thermal touch modes according to different events. When the set condition range is reached, HoloLens sends corresponding instructions to Arduino, and controls the temperature of the heating sheet according to the strength of the instructions to achieve thermal perceptual feedback.

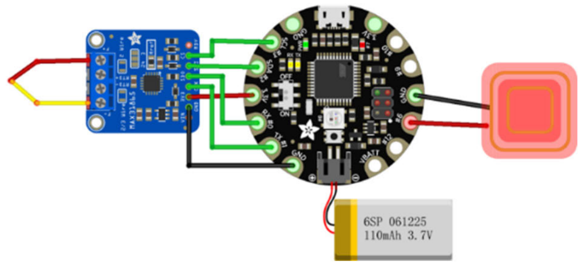

FIGURE 12. Thermal touch sensation module.

C. IMPLEMENTATION PROCESS OF XR CUBE

In the XR upper limb rehabilitation training example, the above eight sensory modules are suitable for all scenarios, including the desktop-grabbing scene, the wall-touching scene, the ball-throwing scene, and the cargo-lifting scene. These four experimental scenarios, as well as the data collection displayed by the Kanban board during the experiment, are shown in Figure 13.

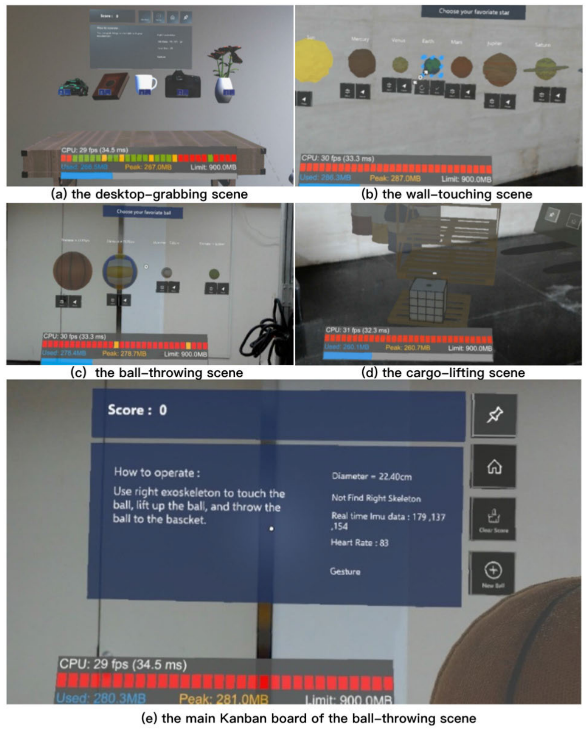

FIGURE 13. Experimental scenarios of XR CUBE.

The use process of posture sensor, pressure sensor, heart rate sensor and sEMG sensor can be summarized as follows: (1) According to key postures in the scenario and the measurement requirements of different sensors, they're placed in specific positions. For example, a posture sensor needs to be placed on the wrist. The pressure sensor should be worn on joints and muscles with significant deformation. The heart rate sensor should be placed on the fingertips, inside or outside the wrist to obtain stable heart rate data through the monitoring of light transmittance. The DFROBOT sensor attaches electrodes to the target muscle, where sEMG is strongest, reducing interference from adjacent muscles; (2) Measure the user's physiological data through the four sensors, including accelerometer data, pressure data, heart rate data, and sEMG. (3) Store the above physiological data in the Bluetooth characteristic and send the data to the HoloLens via BLE. (4) On the HoloLens, the virtual scene and the virtual objects in the scene perform corresponding interactions based on the physiological data. This includes actions such as adjusting the trajectory of a ball or lifting goods, thereby creating a more immersive simulation of the rehabilitation training environment, as well as displaying the real-time heart rate and motion data on the screen of HoloLens.

Placement of vibration sensation based on the characteristics of the object to be simulated, and the vibration motor is triggered by the following three conditions: (1) In the initial state, when the user starts to perform XR upper limb rehabilitation training, HoloLens sends vibration instructions to Arduino. Vibration feedback is used to simulate the operating effect of the driving device when the exoskeleton is turned on, and also serves to remind the user that training is about to begin; (2) When HoloLens detects that the motion state of the manipulated object or exoskeleton in the virtual scene is an upward movement, it sends a vibration command and simulates the activation of the exoskeleton's driving device through vibration feedback, such as, in the ball throwing scene, when the user grabs the ball and raises his hand; in the wall touching scene, when the user raises his arm; in the cargo lifting scene, when the user stands up or bends down while carrying the cargo; (3) When HoloLens detects a collision between an object in the virtual scene and the scene, such as a ball falling to the ground, it sends a vibration command to simulate the interaction effect in the virtual scene through vibration feedback. To make the simulation effect more realistic, the vibration module needs to be placed on the user's calf or foot.

The pressure simulation device is triggered by pressure sensor data greater than the system's preset value at the main movement site on the limb. In the four simulation scenes, the key limb muscle groups of the upper limbs involved in completing the target movements were used to determine the reasonable placement of the pressure simulation device in each scene. In the desktop grabbing scene, the focus is on simulating the internal rotation or external rotation of the wristjoint driven by the forearm muscles. Thus, the pressure simulation device needs to be placed on the wrist; In the wall-touching scene, the focus is on simulating the flexion or extension of the shoulder joint driven by the muscle group near the deltoids of the upper arm. Therefore, the device needs to be placed at the deltoids; In the ball-throwing scene, the focus is on simulating the flexion or extension of the elbow joint driven by the biceps group of the upper arm. In the cargo lifting scene, the focus is on simulating the action behavior of the waist and back muscles, so the device needs to be placed on the back.

Pain sensation and thermal touch sensation are mainly suitable for users who use exoskeletons for a long time in simulation scenarios. The pain simulation device is placed at the key force-generating of limb or at the commonly used muscles to simulate the muscle soreness caused by continuous exercise. While the thermal touch perceptual simulation device is placed at the battery or driver of the exoskeleton to simulate the heat accumulation of the device caused by the continuous operation of the exoskeleton. Additionally, pain sensation can also be used to simulate muscle soreness caused by weight bearing when the user is lifting or throwing heavy objects in the simulation scenario.

Overall, XR CUBE can enrich the intelligence and perception modules of XR devices through sensors and somatosensory simulators, so that diverse tactile stimuli complement the visual and auditory perception that the devices are already equipped with. This improves the overall simulation effect of wearable devices. The modular design of the sensory modules adopts a plug-and-play manner of combination [28]. Each sensory module is independent of each other, has complete functions, and a simple interface. It communicates with HoloLens individually in the form of components without reprogramming or modifying the hardware. At the same time, to facilitate the assembly and storage of multi-module devices, a hexagonal wearable encapsulated box is used. This approach enables any combination of multi-sensory modules to meet diversified prototype simulation needs. Therefore, the sensory module has the advantages of flexibility matching, easy deployment and low application cost. During the actual prototype simulation, users can select appropriate sensory modules (data acquisition device and somatosensory simulation device) based on the experiential demand. These modules can be worn individually or in combination on the body to maintain flexibility and achieve multimodal HCI.

III. XR CUBE STRUCTURE DESIGN

A. PRE-DESIGN OF WEARABLE ENCAPSULATED BOXES

First-generation device is integrated structures. For sensory modules without strict placement requirements or needing proximity, our integrated approach reduces superfluous components. This not only enhances the flexibility of the simulation process but also contributes to weight reduction. After hardware testing, the developed multi-sensory integration module has been able to realize the basic functional requirements. To create a more user-friendly experience, the wearable device is worn directly on the user, allowing for portable multimodal HCI. The development board and the required components are embedded in a wearable encapsulated box, making it a more mature product-level application. The design of the packaging box is based on the main shape of the development board and is established as a rectangular box with length, width and height dimensions of 83mm $\times$ 67mm $\times$ 25.5mm, and a shell thickness of 2.5mm. There are outlet openings for the heart rate sensor, vibration motor, switch and USB communication interface on the four sides of the packaging box, and a deepened groove fitting design is used between the cover and the box body. To obtain accurate heart rate data, the heart rate sensor needs to be fixed on the pulp of middle finger. After many tests and combined with the actual size of the heart rate sensor, the size of the heart rate sensor box is finally determined to be 28mm × 24mm.

Similarly, the size of the vibration module box is determined to be 30mm × 25mm, so that the vibration sensor can be fixed appropriately on the lower side of the arm. In the physical production, Fusion 360 software is first used to model according to the hardware size of the sensory module (Figure. 14a). Secondly, the main encapsulated box, heart rate sensor housing and vibration motor housing are fabricated using 3D printing (Figure. 14b), and heat shrink tubes are used to encapsulate the wires of the heart rate sensor and vibration motor and connect the encapsulated box. Finally, a picture of the Vuforia recognition object is glued to the top of the box and an elastic Velcro strap is glued to the bottom. In practical wear, the encapsulated boxes are attached to the upper side of the wrist of both hands to accurately recognize the physical object, the heart rate sensor is attached to the pulp of the middle finger to obtain accurate heart rate data, and the vibration sensor is attached to the lower side of the arm to convey multimodal perception to the user (Figure. 14c).

FIGURE 14. Wearable encapsulated boxes. a: model drawing of wearable encapsulated boxes; b: physical drawing of wearable encapsulated boxes; c: schematic diagram of the actual wearing of wearable encapsulated boxes.

B. PRE-STUDY OF USERS

Subsequently, we conducted a product trial where 10 participants were invited to complete some simple tasks by using the wearable multisensory integration module. After completing tasks, our researchers conducted an experience interview with the participants to record their feelings during the use of the product. The device will be updated and upgraded based on user trial feedback. A brief description of the product and how to use it were provided to each participant prior at the start of the trial. Some of the participants' interview transcripts were included below:

- *"During the trial, I wore the product to play table tennis. The product brought me a wonderful and realistic game experience. I not only had auditory and tactile perception, but also could feel the vibration feedback of catching the ball…"*
- *"…as I became more proficient in my actions and began to become bolder, I found that the entire operation process became smoother and smoother. Because the device also provides additional tactile feedback, it greatly enhances my real experience during use. For a few moments, I thought I was actually lifting cargo."*

There were also some suggestions:

- *"The device was light enough to wear comfortably on the hand without feeling bulky. However, prolonged use caused some discomfort due to the friction of the Velcro straps against my skin."*
- *"I can wear it anywhere I want, which avoids the more fixed feedback of previous wearables. This means that I can decide which parts of the body I receive sensory feedback from. It would be more ideal if it had multiple modules linking multiple feedback locations."*

Analysis of the collected data and user feedback revealed that the wearable multi-sensory integrated module, fixed directly to the skin, offers simplicity, convenience, and high flexibility and sensitivity. Then, the elastic Velcro straps avoid the discomfort caused by direct contact with the skin. And the elastic material is compatible with most of the experimenters' wrist sizes, which greatly improves the convenience of wearing the device. Secondly, the sensory modules embedded in different boxes can realize the flexibility of wearing parts. While measuring more accurate data, it also improves the wearing comfort experience. It can optimize the appearance of the box to beautify the device, making it more commercialized. Finally, the lightweight device and rich multi-sensory multi-feedback design, supplemented by the holographic image of HoloLens, greatly enhance the user's sense of immersion. The dual feedback mechanism of vision and touch also creates a more perfect experience for users.

However, with the emergence of more diversified application scenarios, researchers have found that the existing devices are difficult to meet the needs of diverse scenarios. Although the integrated combination of wire connections between modules can meet the needs of commonly used sensory modules, it also greatly weakens the independence of each module. Different modules adopt encapsulated box designs with different shapes, which will lead to a single combination of multiple modules, making it inconvenient to store. In addition, the elastic Velcro straps may cause wrist discomfort for long-time wearers.

C. ITERATIVE DESIGN OF MODULAR MULTISENSORY EQUIPMENT

Modular design thinking is a new design idea developed on the basis of the traditional sequential design mode, which is widely used in the field of product design. It is an effective method to coordinate multiple requirements in the design and create multiple overall systems with different forms [29]. Combining the findings of the researchers during the pre-trial and the feedback from users, we decided to use a modularized structural design to iteratively upgrade the existing wearable encapsulated box. Building on the technological foundation of wearable multisensory integration modules, we proposed "XR CUBE," a compact, multisensory, easily wearable, and flexibly combinable sensory augmentation device kit, designed modularly for XR immersive experiences.

The modular design of multi-sensory devices allows the required modules to be easily matched and combined to meet the diverse sensory combination needs of various applications. It can also reduce unnecessary modules and reduce the burden on users. Firstly, to solve the problem that the previous modules cannot be customized, we designed each sensory module as an independent unit. They're encapsulated in separate modular boxes. Bluetooth wireless communication is used between each module. Multi-module collaboration is achieved through plug-and-play connection, which can meet the different combination needs of sensory modules in various application scenarios in XR and greatly improve the user experience. Secondly, we abandoned the quadrilateral design with single connection mode, and design the overall modeling structure of the encapsulated box as a clever hexagon.

The hexagonal shape is a typical reconfigurable structural system [30]. Hence, hexagonal unit modules can meet the needs of individual use of each module and diverse combinations. In terms of assembly, during use, different data acquisition devices and somatosensory simulation devices can be stacked horizontally according to needs to achieve multi-sensory simulation. When not in use, each module can also be stacked vertically to save space, as shown in Figure 15. Third, in terms of the connection method, to maximize the convenience of the connection and disassembly process, we chose the magnetic connection method between each module, which is achieved by attaching long thin magnets to the edges of the hexagon. Finally, the sensory modules can be worn anywhere on the user's body. The silicone wristband and nano-washable double-sided adhesive are used to fix the sensory module placed on the surface of the user's limbs and torso. The silicone wristband and nano-sized double-sided adhesive tape can ensure the comfort of wearing, so that the user will not feel uncomfortable after wearing for a long time.

FIGURE 15. Diagram of XR CUBE assembly method.

Based on the above modular idea, we used the 3D printer in the laboratory to produce a simple prototype, as shown in Figure 16. The XR CUBE is an advanced design from lab-level research to user-oriented product level, which is ultimately expected to be a peripheral device for the XR headset.

FIGURE 16. 3D printed prototype of the XR CUBE.

D. USER STUDY FOR ITERATIVE DESIGN

We conducted a product test as we did with the first-generation product, in which we invited 10 participants who had previously participated in the pre-trial of the first-generation product to complete the same tasks as before using the XR CUBE. After completing the tasks, our researchers conducted another interview with them to record their relevant feelings during the use of the product:

- *"The XR CUBE represents a substantial advancement in immersion and wearing comfort over the first generation. While the first generation reduced the size of the encapsulated boxes, its wired connections still hindered hand movements. The XR CUBE overcomes this by achieving true modularity."*
- *"Its expanded range of sensory modules, including new ones for pain and thermal touch sensations, enhances the immersive experience, allowing for the simulation of more diverse scenarios."*
- *"A notable enhancement is the use of silicone wristbands and nano-double-sided tape for module attachment, significantly reducing wear fatigue even during extended use."*
- *"The XR CUBE's distinct, uniform hexagonal design conveys a sense of a mature product. Its modules, now connected via Bluetooth, offer greater independence and varied combinations. The enriched range of modular sensory modules provided a more nuanced perception during the basketball game."*
- *"The XR CUBE has significantly expanded my concept of virtual interaction beyond the impressive previous generation. Its immersive experience, coupled with a neat hexagonal design reminiscent of Lego, makes assembling and disassembling the device enjoyable and convenient for storage."*

IV. APPLICATION PROSPECTS

A. FUNCTIONS AND APPLICATIONS OF EACH MODULE

Modular design is manifested in each module being a subsystem with a specific function. These subsystems, as universal modules, can be combined with other functional modules in various ways to form new systems with diverse functionalities, thereby enabling product serialization [31]. Therefore, each sensory module in the XR CUBE is an independent data acquisition unit or somatosensory simulation unit that provides sensory support for various applications of XR to realize an immersive experience with multi-sensory inputs. The selection of sensory modules mainly adopts the analytical hierarchy process (AHP) multi-criteria decision analysis [32] method (Figure 17) to analyze the key functional objectives in various applications of XR based on the QFD method, and transform these key requirements into corresponding functional characteristics [33]. Firstly, the three main types of interactions in XR application scenarios are summarized: immersive experience (scenario simulation) [34] inter-experience (teaching and training) [35], and primary-secondary experience (remote operation) [36]. Then the nine typical application fields of XR are identified, and the key types of thematic application projects within each field are analyzed to summarize 18 representative types. Finally, the weight level of each functional requirement is calculated from the three first-level indicators of necessity, effectiveness and ease of use, and six second level indicators of utilization rate, impact, prototype simulation capability, scenario simulation capability, development difficulty and operability. Fourteen sensory modules with development value are preliminarily determined, which are 8 modular data acquisition units and 6 somatosensory simulation device units.

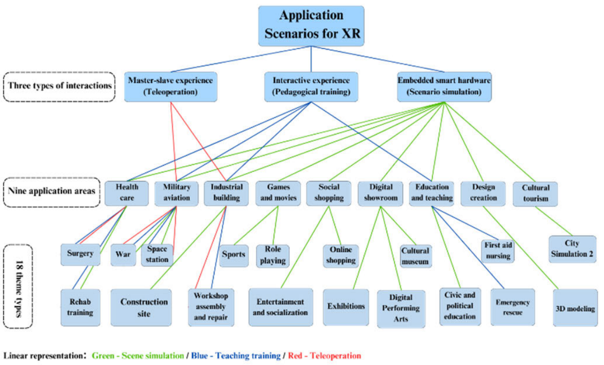

FIGURE 17. Sensory module selection.

The modular data acquisition unit mainly acquires the user's physiological data through sensors to realize smarter interaction with the XR environment. And the eight sensors are: posture sensor, pressure sensor, heart rate sensor, myoelectric sensor, bending sensor, angle sensor, GSR sensor, temperature sensor, and Hall sensor. Among them, the heart rate sensor, myoelectric sensor, GSR sensor, temperature sensor, and Hall sensor need to be in direct contact with the user's skin.

The somatosensory simulation device unit is mainly used to provide sensory stimulation to the skin at a specific location to realize the effect of multi-sensory experience in the XR environment. Six sensory modules are: vibration sensation, acupressure sensation, pain sensation, thermal touch sensation, kneading sensation, and pushing and kneading sensation.

FIGURE 18. Sensory module body wear position diagram.

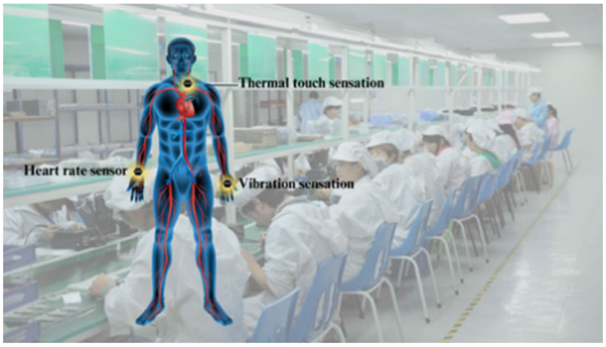

FIGURE 19. Teaching and training scenario: assembly-line work.

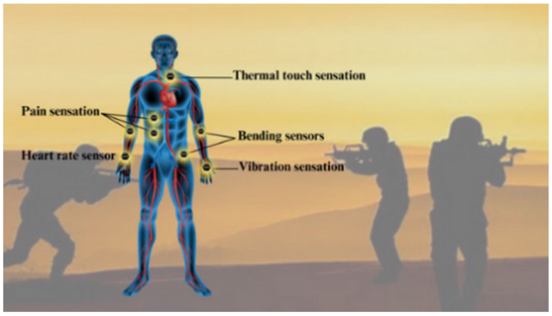

FIGURE 20. Military scenario: military outreach training.

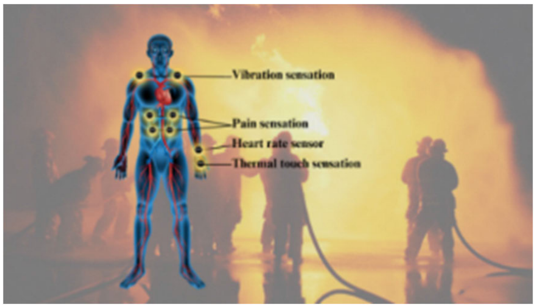

FIGURE 21. Virtual drill scenario: fire emergency rescue.

B. APPLICATION SCENARIOS OF WEARABLE MULTIMODAL INTELLIGENT INTERACTION DEVICES

XR CUBE adopts a modular multi-sensory feedback approach worn on the user (Figure 18) and is designed to enhance the immersion of the user experience in XR environments. A series has more than ten modules, each representing a different perception, which can communicate with the XR scene wirelessly via Bluetooth, and each module realizes multi-module synergy through plug-and-play technology. The modularized structure has the following advantages: (1) It can be arranged and combined by modularization to meet the various needs of different virtual scenes; (2) The wearable and miniaturized design concept allows the module to be placed anywhere on the body to achieve different

FIGURE 22. XR CUBE applications in 8 classic scenarios.

functional requirements and is easy to use; (3) Users can personalize module selection according to their preference, even within the same application scenario.

1) TEACHING AND TRAINING SCENE

In the field of teaching and training, XR CUBE's multi-module construction can meet the application needs of many education, training and other scenarios. XR CUBE will change the way users access knowledge with the help of rich sensory modules and somatosensory simulation devices.

In industrial training, such as assembly line worker training, XR CUBE detects workers' postures through bending sensors and assesses fatigue via heart rate sensors (Figure 19). It provides feedback on incorrect postures through vibration sensations and suggests breaks based on continuous work duration using varying vibration frequencies and thermal sensations. Considering that driving learning is dangerous and requires real-time monitoring of students' driving posture and fatigue. XR CUBE can also be used in car driving learning in the same way.

2) MILITARY SIMULATION SCENARIOS

In the field of military simulation, many training scenarios need to restore the true training process to the greatest extent while ensuring the safety of soldiers.

Take the real-person CS (Counter-Strike) field battle in military expansion training as an example (Figure 20). The vibration module can be used to simulate the moment when the soldier pulls the trigger and the bullet flies away from the gun barrel towards the target. The soldier's incorrect combat posture can be corrected by bending sensor, and the low-frequency electric pulse muscle stimulation in the stronger mode can be used to simulate the soldier being hit by the bullet. The pain of the hit, and the psychological condition of the soldier are assessed through the heart rate sensor.

3) VIRTUAL REHEARSAL SCENARIOS

If disaster scene drills use real scenes as the drill venue, it will cause great safety hazards to the participants. However, with the help of XR CUBE, simulation exercises of disaster scenarios can be realized, while the personal safety of participants can be greatly ensured.

In fire emergency rescue simulations, XR CUBE enhances the realism and immersion of drills (Figure 21). The thermal touch module simulates the high temperatures of a fire scene, while vibration feedback replicates the sensation of a building collapsing. Additionally, using low-frequency electrical pulse muscle stimulation for pain perception module mimics the stinging sensation of burns, and a heart rate sensor tracks psychological changes in trapped individuals. These sensory modules and devices collectively create a lifelike fire scenario, significantly improving participant engagement and the overall effectiveness of the training exercise.

4) GAME ENTERTAINMENT SCENE

In gaming and entertainment, XR CUBE allows players to assemble various modules for different game scenarios. Its multi-sensory modules not only collect movement and physiological data but also enrich in-game character experiences through somatosensory simulations.

Below we will take eight typical scenes in the action and racing games as examples to introduce the application of XR CUBE (Figure 22).

Take the shooting and racing scene as examples, different temperature feedback will simulate the distance between the bomb explosion point and its own position in the game. Besides, we can install the thermal touch sensation on the arm to simulate the exhaust heat caused by vehicles passing by.

Take the kicking, mountain climbing and snowball fight scene as examples, acupressure sensation is mainly used to feedback the sensation of the end of the limb. Thus, it can be used to simulate the feeling of feet being pressed and squeezed by the soccer ball. And in the mountain climbing scene, it can simulate the feeling of grabbing and stepping on the mountain. At last, in the snowball fight scene, it can simulate the player's feelings when kneading and holding the snowball.

Take the dance and skiing scenes as examples, we can install posture sensors and angle sensors on key joints such as wrists and ankles of the body to collect the player's movement data immediately.

Take the shooting, snowball fight and boxing game scenes as examples, supplemented with pain sensation, the vibration sensation feedback and electrical stimulation in weaker modes simulate the feeling of hitting caused by different bullets, snowballs, and opponents. Besides, take the racing, skiing and mountain climbing scenes as examples, the vibration sensation can be used to simulate the rough road and mountain conditions.

Heart rate sensor and vibration sensation are suitable for all scenarios. The heart rate sensor on the wrist is used to monitor the player's physical state and remind the player to pay attention to rest in time. The vibration sensation is installed on the back, arms and legs to simulate the contact between objects and players in different scenarios, as well as the physical collision between players.

V. DISCUSSION AND CONCLUSION

As an immersion-enhancing module set, XR CUBE can greatly improve the user's immersion. The modular design also greatly meets the diverse needs of XR devices in today's market. The main functions are twofold. On the one hand, based on the collection of user data from multiple sensors, including physical data such as posture and pressure, as well as physiological signals like heart rate and sEMG, the data is processed and analyzed to achieve human action recognition and user behavior detection. This enables a deeper level of natural interaction between users and XR scenarios; On the other hand, based on the multi-sensory feedback from tactile simulation devices, such as vibration, acupressure, pain, thermal sensation, and other sensory channels, extending beyond the visual and auditory perception provided by XR devices, provides users with a multidimensional, enhanced sensory experience at the physical level.

However, there is still some room for further expansion and improvement in terms of power, ergonomics and intelligence for XR CUBE. First of all, to maximize the portability of wearable devices, the device is often compressed, which brings the problem of device power supply. Many sensors, such as heart rate sensors and angle sensors, need to work continuously for a long time. The weak power storage capacity makes it difficult to support the device's prolonged operation, which will cause greater inconvenience to the user if it is repeatedly taken off and put on. Secondly, due to the skin-friendly contact method of XR CUBE, the ergonomics of the device also need to be considered. With the development of new materials, it can use lighter and smarter materials to further improve the user's wearing experience. Thirdly, if the complexity of future tasks increases, we will consider using hardware devices capable of running deep learning models while still maintaining relatively low latency and power consumption. With the rapid development of materials science, nanotechnology, communication technology and biotechnology, XR CUBE has broader development prospects and room for improvement. It can be integrated into various fields of our lives and work in different ways. People have a new definition of the virtual world and have put forward new demands for immersive augmented reality.

Overall, we have successfully built an XR sensory device, "XR CUBE", which is multimodal, wearable, modular and intelligent. In particular, we embedded sensory modules and somatosensory simulation devices into physical wearable devices and achieved personalized customization of wearable devices through modular design. Users can combine the sensory modules in "XR CUBE" in different ways and apply them to different experience scenarios to achieve personalized customization of wearable devices. Through tests by volunteers, it's found that "XR CUBE" can indeed greatly improve the user's immersion. The modular design method also breaks through the limitations of existing integrated wearable devices and greatly expands the application scenarios of the device kit.

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