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Design of haptic interaction products based on virtual reality

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Abstract. With the development of virtual reality technology, the traditional interaction methods dominated by vision and hearing can no longer meet users' demands for immersive experience, and haptic interaction has gradually become an important means to enhance the realism of virtual environments. From the perspective of product design, this paper extracts the haptic information requirements in the process of virtual reality interaction through market analysis and user research, and sorts them by priority. On this basis, a design scheme of a split-type haptic interaction glove combining a fingertip haptic module with a dorsal hand control unit is proposed. Adopting a modular structure, the scheme realizes haptic feedback functions such as interaction confirmation, event prompt and navigation guidance, which improves wearing comfort and operational freedom while ensuring haptic perceptibility, and provides a reference for the lightweight design of virtual reality haptic interaction products.

Keywords: virtual reality, haptic interaction, wearable devices, haptic gloves, modular design

1. Introduction

In recent years, Virtual Reality (VR) technology has developed rapidly. Its basic principle is to build a virtual environment that can provide users with an immersive experience based on computer information technology, combined with various scientific and technological achievements such as 3D graphics technology, multimedia technology and display technology. With technological advancement, virtual reality has gradually evolved from a single sensory experience dominated by vision and hearing to an interactive form of multi-sensory fusion, which is regarded as one of the important development directions to enhance the immersion and realism of virtual reality [1]. At present, virtual reality technology has been widely applied in various fields such as industrial manufacturing, education and training, product design, medical rehabilitation, and cultural entertainment. Driven by the concept of the metaverse, as its core supporting technology, virtual reality technology puts forward higher requirements for users' interactive experience in virtual environments.

Existing virtual reality systems still mainly rely on visual and auditory channels in practical applications. Users often lack corresponding haptic feedback when operating virtual objects, which restricts the authenticity and immersion of the interactive experience. Relevant studies have shown that haptic feedback plays an important role in enhancing users' sense of presence in the virtual environment and improving the realism of operations, and it is an important component of constructing a highly immersive virtual reality experience [2].

To make up for the lack of haptic information in virtual reality interaction, haptic interaction technology has gradually become a research hotspot in recent years. Among them, hand-based haptic interaction has significant advantages in virtual reality systems because it conforms to human natural operating habits. As a typical wearable haptic interaction device, haptic gloves can capture hand movements and output multi-point haptic feedback, showing good application potential in scenarios such as virtual operation, virtual training and immersive experience [3]. Hand-based haptic interaction has distinct advantages due to its consistency with human daily operating habits. As a wearable interactive device acting directly on the hand, haptic gloves can combine hand motion capture with multi-point haptic feedback without occupying additional operating space, and are regarded as an important carrier for achieving highly immersive virtual reality interaction. However, existing haptic gloves still have deficiencies in terms of wearing comfort, interaction naturalness, forms of haptic feedback expression and system integration, which need further research and optimization from the perspectives of product design and system design.

Therefore, conducting a systematic design research on VR-based haptic interaction glove products from a design perspective, combining virtual reality technology with the principles of haptic interaction, is of great significance for improving the virtual reality interactive experience, enriching the forms of haptic interaction products and promoting the application and development of virtual reality technology.

At present, flexible haptic actuators mainly adopt the following driving mechanisms: fluid actuation (pneumatic/hydraulic), magnetic actuation, optical actuation, thermal actuation and voltage actuation. Typical cases are as follows: the haptic sleeve equipped with pneumatic actuators developed by Cosimadu Pasquie, which can provide pressure feedback with millimeter-level precision [4]; the biomimetic skin prototype based on hydrogel by Yuta Dobashi, which realizes haptic sensing by using the piezoelectric effect [5]; the cobalt-based microfilament sensing and driving system by Hauser H., which achieves a low detection limit and a wide working range through the Giant Magnetoimpedance (GMI) effect [6]; and the Liquid Crystal Elastomer (LCE) display by C.J. Camargo, which controls surface deformation by using near-infrared light to realize pressure and vibration feedback synchronously [7].

Voltage-driven actuators have outstanding performance in improving the immersion and real-time performance of human-computer interaction due to their advantages such as fast response, low power consumption, lightweight and high-precision control. The current mainstream voltage-driven haptic actuators mainly adopt Ionic Polymer-Metal Composites (IPMCs) [8], Dielectric Elastomer Actuators (DEAs) [9] and flexible piezoelectric materials [10]. For example, Qiao H. introduced a periodic stiff rib structure into the IPMC-hydrogel composite material through modulus gradient design, which effectively suppresses tensile interference to achieve distortion-free sensing [11]; the PVCF-based dielectric elastomer developed by Huang J. significantly improves driving efficiency by virtue of its high dielectric constant and low viscoelastic loss [12]. Nevertheless, existing dielectric elastomers and IPMCs still have limitations in terms of durability, safety and cost-effectiveness in high-frequency human-computer interaction scenarios. The VR environment requires accurate haptic feedback and wearing comfort under frequent interactions, which poses severe challenges to the research and development of haptic actuators.

The Howe team was the first to apply PVDF materials to robotic finger sensors for surface feature and texture analysis [13]. Dargahi from Simon Fraser University in Canada analyzed the piezoelectric and pyroelectric properties of PVDF films and tested their dynamic response [14]. Experiments showed that piezoelectric and pyroelectric excitations can be distinguished according to the transient response characteristics, that is, from piezoelectric, piezoelectric-pyroelectric hybrid to pure pyroelectric response, the rise and fall times of transient response signals increase gradually. Furthermore, a haptic sensor composed of three PVDF films was proposed [15]. Polyvinylidene Fluoride (PVDF), a flexible piezoelectric material, has become a key material in the field of haptic actuation due to its soft, ultra-thin and durable characteristics [16-20], and is the best choice for manufacturing haptic feedback actuators.

2. Relevant theories and research framework

2.1. Virtual reality

A virtual reality system is an integrated technical system that constructs an immersive virtual environment through computer technology and enables users to interact with the virtual world in a natural way [21]. Its core goal is to provide users with a real, intuitive and immersive interactive experience through the fusion of multi-sensory information. Generally speaking, a virtual reality system mainly consists of three parts: hardware system, software system and interaction system. The hardware system of a virtual reality system is mainly used for the input and output of virtual environment information, and is the foundation for realizing an immersive experience. Common hardware devices include Head-Mounted Displays (HMD), position and posture tracking devices, handheld controllers and haptic feedback devices. The head-mounted display is responsible for presenting stereoscopic visual information to users; the position and posture tracking devices are used to obtain real-time motion data of users' heads and bodies; and the hand interaction devices and haptic devices are used to realize more natural operations and feedback. The software system is the core of the operation of a virtual reality system, mainly including virtual scene modeling, rendering engine, physical simulation module and interactive logic control module. Through the calculation of 3D models, materials, lighting and physical properties, the software system can generate a virtual environment matching user behavior in real time and trigger corresponding interactive feedback according to user input. The interaction system is an important bridge connecting users and the virtual environment, whose main function is to realize the recognition, analysis and feedback of user behavior. By collecting users' movements, postures and operational intentions, the interaction system converts them into interactive instructions in the virtual environment, and feeds back the interaction results to users through vision, hearing or touch [22].

2.2. Research on the application status of haptic interaction in product design

With the gradual development of human-computer interaction methods from the traditional vision and hearing dominance to multi-sensory fusion, haptic interaction, as an important medium connecting users and products, is gradually becoming an important direction in product design research. By providing users with feedback information such as force, vibration and pressure, haptic interaction enables users to obtain a more real and intuitive perceptual experience during operation, and has significant advantages in improving product usability, immersion and emotional experience.

2.2.1. Vibration

Vibratory haptic stimulation can cause skin deformation, which is then perceived by mechanoreceptors, and it is the most common haptic feedback method in electronic devices at present. As shown in Figure 1, the perception of vibratory haptics is determined by three factors, including spatial factors, temporal factors and intensity factors [23].

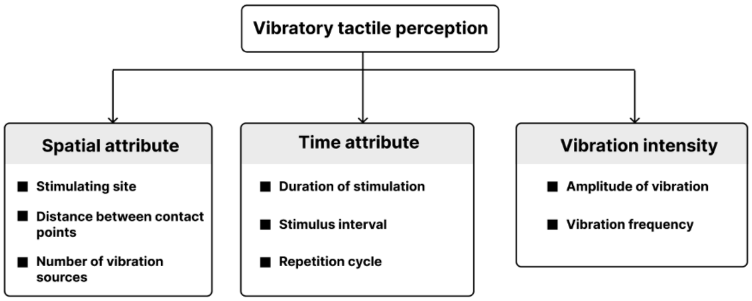


Figure 1. Three elements of vibratory haptic perception

The application of vibration feedback on mobile terminals such as mobile phones and smart watches has been quite mature, and it is also the first force feedback method applied to VR devices (controllers). In electronic products, cam rotor motors and linear resonant actuators are mainly used to generate vibration.

Linear resonant actuators feature fast response and almost no delay, which significantly improve the quality of interaction. The vibration feedback mechanism is widely used in interactive devices due to its simple structure and easy information transmission through skin contact. Especially in the field of virtual reality, the Hyper Sense controller equipped on the VR all-in-one machine PICO4 (Figure 2a) has a built-in wide-frequency linear resonant actuator with a frequency range of 50-500Hz, which can provide vibration feedback of varying intensities and greatly enrich users' haptic experience. In addition to traditional controllers, the Tact Suit haptic suit launched by the South Korean company Haptics (Figure 2b) further demonstrates the potential of vibration feedback technology. The suit includes a vest, gloves and a face mask, with multiple vibrators embedded in each part, which can generate vibrations at the corresponding parts according to the impact received by the game character in virtual reality games. For example, in a VR game simulating firearm shooting, in addition to the vibration of the hand controller, the Tact Suit also generates vibration on the player's upper chest to simulate the recoil force on the shoulder after the firearm is fired. This multi-part, precise haptic feedback adds a new dimension to the virtual reality experience, enabling users to feel a more realistic interactive effect [24].

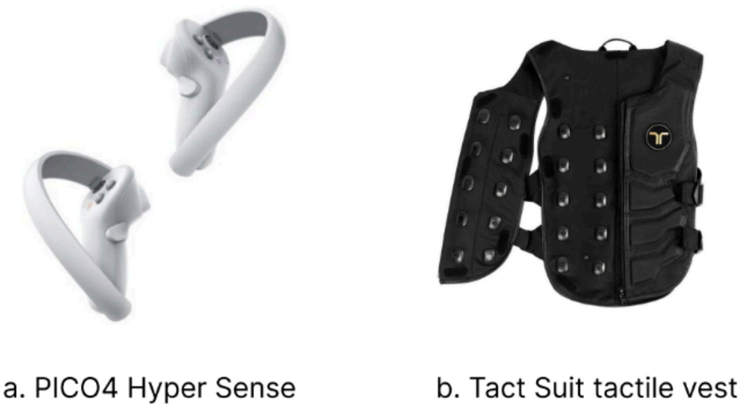

a. PICO4 Hyper Sense
b. Tact Suit tactile vest

Figure 2. Application of vibratory haptic feedback products

2.2.2. Force feedback

Force feedback devices refer to devices that apply a certain constant force to specific parts of the human body to simulate the reaction force received by the human body when performing the same operation in the real world. Research on force feedback suits for virtual reality is developing rapidly. In the research of force feedback devices, the first method applied is to apply pressure to local parts of the human body, such as the Meta airbag gloves shown in Figure 3a. The gloves are embedded with multiple airbag pads distributed in ridges along the fingers, with about 15 independent airbags in each pad. When users wear the gloves and participate in VR or AR experiences, the system adjusts the air pressure of each airbag according to the interactive scene, thus generating varying pressure sensations in different areas of the hand. To achieve mechanical balance, when the device needs a certain part of the palm to bear pressure, the other parts of the palm will also generate corresponding reaction forces. As shown in Figure 3b, Microsoft has cleverly utilized this principle to invent a VR accessory PIVOT for the hand. As shown in the figure, the device includes a wearing part, a force-applying component connected to the wearing part and a haptic feedback device. The lever supported by the frame of the haptic feedback device can be coupled with the force-applying component. When a player grasps an object in a virtual scene, the spherical PIVOT on the device gently strikes the user's palm and applies pressure to the surface of the body part to simulate the mechanical effect of grasping an object with the palm [25].

a. Meta airbag gloves

b. PIVOT

Figure 3. Application of force haptic feedback products

2.3. Analysis and shortcomings of VR haptic interaction products

With the development of virtual reality technology, haptic interaction has gradually moved from laboratory research to practical product applications, forming various types of VR haptic interaction products such as vibration feedback controllers, haptic gloves, force feedback devices and multi-modal haptic suits. These products have achieved certain results in enhancing the immersive experience of virtual reality, but from the perspective of product design and user experience (Table 1), there are still many deficiencies.

Table 1. Analysis of existing VR haptic interaction products

Product Type	Typical Products	Main Haptic Forms	Advantages	Limitations	Notes
Vibration feedback	VR controllers, vibration bracelets	Vibration	Low cost, high stability, high maturity	Single haptic form, weak realism	Difficult to simulate real grasping and mechanical characteristics
Force feedback	Airbag gloves, mechanical force feedback devices	Pressure/ resistance	Strong realism, high immersion	Large volume, complex structure	Poor wearing comfort, low universality
Haptic gloves	Fingertip/hand haptic gloves	Vibration/ pressure	Natural operation, precise interaction	Need to balance feedback and comfort	Require further systematic design and optimization

3. Research methods

This research takes the user demand-oriented product design process as the core, takes market analysis and user research as the main sources of demand extraction, and forms design objectives and constraints accordingly. It mainly includes the following four steps: Market analysis (secondary information) combs the development trends of VR technology and immersive interaction by consulting industry research reports, enterprise white papers, academic papers and relevant product materials, analyzes the market status, typical application scenarios and main pain points of haptic interaction products, and identifies the potential opportunities and application value of haptic interaction in the field of virtual reality.

User research (primary information) focuses on the interaction process and haptic needs of users with immersive experience, adopts a combination of questionnaire survey and semi-structured interview to collect users' interaction problems, information acquisition methods, haptic preferences and wearing comfort expectations during VR use, so as to form a quantitative and qualitative understanding of real user needs.

3.1. Market analysis

With the rapid iteration of computer graphics, sensors and display technologies, Virtual Reality (VR) devices have gradually moved from the laboratory to the consumer market and expanded to diversified application fields such as education and training, cultural tourism experience and simulation training. In recent years, the VR/AR/XR head-mounted display market has continued to evolve in terms of shipment volume, industrial structure and application ecology, and mainstream research institutions still pay close attention to its long-term development [26, 27]. Compared with traditional screen interaction, the core value of VR lies in enabling users to obtain a stronger sense of spatial presence and participation through the construction of an immersive environment. However, the current mainstream VR interaction is still dominated by vision and hearing with weak haptic feedback, which restricts the real perception and interaction credibility in the virtual environment. Based on this, this section carries out analysis from three levels: market development trend, interaction technology evolution and haptic product status, providing a basis for subsequent user research and demand extraction.

In recent years, VR hardware products have been continuously optimized in terms of display effect, tracking accuracy and interaction methods, with typical manifestations as follows: head-mounted display devices are gradually developing towards higher resolution, lower latency and lighter weight; spatial positioning and hand tracking capabilities are constantly improved, laying a foundation for natural interaction. The tracking research on the AR/VR head-mounted display market by the International Data Corporation (IDC) shows that although market growth will be affected by factors such as price and content ecology in some stages, the demand for head-mounted displays still has growth drivers in the future with the decline of hardware costs and the improvement of functions [27-29]. In addition, the XR/VR tracking report by the market research institution Counterpoint points out that the VR market pattern has phased fluctuations in recent years, but it will be driven by more usable product forms and content applications in the future [30, 31]. From the perspective of the industry, factors such as the decline in AI computing power and costs are also considered likely to drive the increase in demand for AR/VR devices [32].

From the perspective of market demand, the growth of immersive content and the improvement of user experience expectations have made the VR interaction method show a trend of shifting from operation-oriented to experience-oriented: users are no longer only satisfied with completing instruction input through controllers, but more eager to obtain interactive feedback in line with real-world laws, such as the sense of contact when touching objects, changes in resistance during operation and spatial direction prompts. This trend has also promoted the gradual development of VR interaction systems towards multi-modal fusion, that is, the collaborative integration of visual, auditory and haptic feedback channels to improve the realism and immersive experience of interaction. Research institutions such as Deloitte have pointed out in their research on VR industry applications and training that VR is moving from traditional entertainment to more industrial application scenarios, and the requirements for interaction and feedback in real training and immersive experience are further improved [33, 34].

In general, the development trend of the VR industry can be summarized as: hardware performance improvement—application scenario expansion—enhancement of user experience expectations. Against this background, haptic interaction, as a key link to "fill the short board of immersive experience", is gradually highlighting its application value.

3.2. User research

The questionnaire was distributed through the online platform Wenjuanxing, with a total of 60 questionnaires collected, all of which were valid samples after screening (N = 28). The samples cover different levels of VR use frequency, which can form a relatively comprehensive preliminary judgment on haptic feedback preferences and product form acceptance. Due to the relatively limited sample size, this research mainly adopts descriptive statistics in data analysis without significant inference, focusing on extracting design requirements and insights to serve subsequent product design.

3.2.1. Questionnaire design ideas and structural dimensions

The questionnaire design constructs its structure around the logic of VR interaction pain points—haptic needs—wearing preferences—product acceptance. Combined with the design focuses of the haptic interaction product in this research (fingertip haptic module, haptic prompt, navigation guidance, etc.), it sets 27 questions in five modules, mainly including: basic information and VR use background, VR interaction pain point assessment (scale questions), haptic feedback needs and preferences, wearing form and modular demand, and open-ended questions (Table 2).

Table 2. Questionnaire structure and dimension setting

Module	Research Content	Main Output
Basic information	Gender, age, VR experience, use frequency	Sample background and grouping basis
Interaction pain points	Difficulty in positioning, UI dependence, interaction confirmation, immersion interference, sound reliability	Pain point ranking and haptic intervention opportunities
Haptic needs	Recognition of haptic value, scenarios of haptic occurrence, acting parts, direction prompt methods	Haptic functional requirements and feedback strategies
Wearing preferences	Choice of wearing form, acceptance of modularization, wearing concerns	Appearance and structural design constraints
Open-ended questions	Suggestions/concerns/expectations	Supplementary insights and design implications
Module	Research Content	Main Output

3.2.2. Data processing and analysis methods

This research mainly adopts descriptive statistical analysis for the questionnaire results, including statistics of frequency, proportion and mean (Likert Scale questions), and sorts the selection proportion for multiple-choice questions. Combined with the content of open-ended questions, the keyword induction method is used to extract users' core concerns about haptic interaction products (such as comfort, sense of restraint, safety, etc.), which is compared and verified with the quantitative statistical results.

3.3. Extraction and prioritization of information requirements

Based on the user research results (see Appendix), this research further converts users' pain points and haptic preferences in immersive VR experience into haptic interaction information requirements, and sorts the requirements by priority, thus providing a basis for subsequent product function design, haptic feedback strategies and structural scheme determination. The demand extraction follows the logic of Scenario-Task-Information-Haptic Presentation: that is, identifying key information types starting from users' typical tasks, and then mapping the information types into executable haptic feedback strategies.

3.3.1. Extraction and classification of information requirements

According to the statistical results of the questionnaire on "the scenarios where haptic feedback is most expected to appear", users' demands for haptic feedback are mainly concentrated in two categories: interaction confirmation feedback and event prompt feedback (both with a selection proportion of more than 60%), followed by information types such as navigation direction prompt and approaching target reminder. Therefore, this research classifies haptic interaction information requirements into four categories: interaction confirmation information, event prompt information, navigation guidance information, and status and progress information.

Table 3. List of haptic interaction information requirements and haptic presentation strategies

Information Category	Typical Demand Sources	Examples of Information Content	Haptic Presentation Suggestions	Design Significance
Interaction confirmation	Button/switch confirmation (67.9%), touch and grasp confirmation (60.7%)	Successful touch, successful grasp, button trigger, switch switching	Mainly short and clear vibration with a "sense of confirmation"; it is recommended to form memory with a unified rhythm	Improve interaction reliability and immersion (core function)
Event prompt	Collision/impact prompt (64.3%)	Being hit, danger approaching, environmental impact	Express the urgency with higher intensity/more rapid rhythm	Strengthen situational feedback and improve reaction efficiency
Navigation guidance	Demand for direction prompt (35.7%)	Forward/stop/left/right, etc.	Express directions with combinations of different fingers or rhythm coding (it is recommended to be redundant with vision)	Support exploration tasks and guide user behavior
Status/progress	Approaching key targets, task completion, etc. (relevant options in Q13)	Arriving at nodes, task completion, discovering targets	Distinguish status changes with slight prompt vibration/gradual increase and decrease in intensity	Transmit information with low interference and reduce UI dependence

Based on the above classification, this research sorts out the list of haptic interaction information requirements combined with the questionnaire results (Table 3).

3.3.2. Demand prioritization (MoSCoW method)

To convert information requirements into executable product design and development plans, this research adopts the MoSCoW method to sort the requirements by priority, dividing them into four categories: Must have, Should have, Could have, and Won't have this stage. The basis for priority ranking includes: user selection proportion and importance (confirmation feedback and event prompt are the highest), product positioning (lightweight fingertip module haptic interaction), technical implementation complexity and system scalability, and the direct degree of improving immersive experience. The final ranking results are shown in Table 4.

Table 4. Haptic interaction requirement priority matrix (MoSCoW)

Priority	Requirement Type	Corresponding Information Type	Design Focus
Must	Operational Confirmation Feedback (Triggered by Touch/Button/Grab)	Interaction Confirmation	Standardize the tactile mode; Synchronize tactile feedback with interaction events; Ensure rapid response
Must	Collision/Impact/Event Reminder Feedback	Event Prompt	Differentiate emergency levels by intensity/rhythm; Ensure it is clearly perceivable
Must	Comfortable to Wear, Low—restraint, Light—weight	Structural/Experience Requirements	Finger—tip modular wearing, reduce coverage area, optimize flexible materials and wiring
Should	Adjustable Tactile Intensity (For Different User Sensitivities)	System Parameter Requirements	Provide multiple intensity/frequency configurations; Map parameters on the software side
Should	Navigation Direction Prompt (Instruction Coding)	Navigation Guidance	Use finger combinations/rhythms for coding; Redundantly prompt with visual UI
Could	Task Progress/Node Arrival Prompt	Status/Progress	Scene events trigger tactile prompts, reducing reliance on visual pop—ups
Could	Module Replaceability and Expandability (Replacement of Different Types of Actuators)	Expandability Requirements	Modular interface structure, detachable and replaceable finger—tip tactile units
Won't	High—fidelity Tactile Sensation at Multiple Points on the Whole Hand/Body, Complex Force Feedback	Multi—modal Fidelity Requirements	High R & D costs, complex structure, exceeding the product—oriented positioning of this research

3.4. Design objectives

The questionnaire results show that users have the highest demand for operational confirmation haptic feedback (67.9% for button/switch operation confirmation and 60.7% for touch and grasp confirmation). Therefore, this research takes haptic feedback for interaction confirmation as the core functional objective of the product. The product should be able to provide immediate, clear and identifiable haptic feedback when users touch, grasp, press or trigger virtual interactive events, enabling users to confirm the success of interaction without relying on visual pop-ups.

Users have a relatively high demand for event prompts such as collision/impact (64.3%), indicating that haptic feedback is not only used for operation confirmation but also undertakes the role of situational enhancement. Therefore, the product needs to have the ability of haptic feedback for virtual environment events (such as collision, danger prompt, task trigger, etc.), and express different event levels through differentiated haptic modes, so as to improve the realism and real-time performance of the immersive experience.

Although the demand proportion for path navigation/direction prompt is relatively low (35.7%), a certain number of users recognize the haptic guidance method, and direction guidance has obvious value in exploration scenarios. Therefore, the product should have the ability of haptic information coding, for example, expressing direction instructions (forward/stop/left/right, etc.) through combinations of different fingers, rhythms, durations, etc., and support redundancy with visual prompts to improve the reliability of information transmission.

The survey on wearing preferences shows that users prefer the fingertip cot module wearing method (53.6%), and are most concerned about the sense of restraint, stuffiness and weight. Therefore, the product should adopt a partial wearing strategy to avoid full hand coverage, reduce volume and weight, reduce movement restrictions, improve air permeability and comfort, and support continuous experience for a certain period of time.

Different users have differences in haptic sensitivity, so the product needs to support the adjustability of haptic intensity and frequency to meet the needs of individual differences and improve adaptability. In addition, the modular structure should support the replacement and upgrade of subsequent actuators, laying a foundation for product iteration.

4. Product design

4.1. Product design positioning

Based on the previous analysis of the development status of virtual reality haptic interaction technology, user needs and system design, this research positions the product as a wearable haptic interaction glove for immersive virtual reality application scenarios. With the core goal of improving the haptic perception ability in the process of virtual reality interaction, the product focuses on the perceptibility of haptic feedback, wearing comfort and the rationality of system integration, and is suitable for application scenarios such as virtual exploration, immersive experience and interactive guidance.

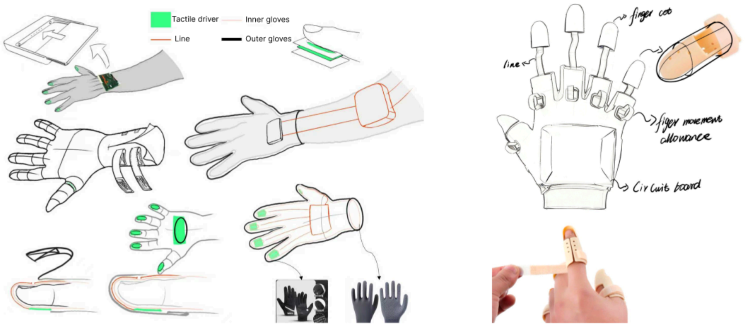
From the functional level, the haptic interaction glove takes hand and fingertip haptic feedback as the main interactive output mode, and conveys touch, prompt and guidance information in the virtual environment by arranging haptic drive units at key parts such as fingertips and the dorsal hand. At the same time, the overall structure of the glove needs to match the interaction logic of the virtual reality system, and can provide stable and clear haptic feedback without interfering with users' visual and operational behaviors.

In terms of design concept, the product adopts the design idea of modular haptic unit + double-layer glove structure. Haptic actuators and control circuits are integrated into the glove in the form of modules, and the restriction on hand movement is reduced through a reasonable arrangement method; the outer glove is used to protect electronic components and improve the overall durability, while the inner glove emphasizes fit and comfort, enabling haptic feedback to act on the skin surface more directly. This structural form helps to improve the wearing stability and comfort for long-term use while ensuring the haptic effect.

In terms of modeling and visual expression, the overall style of the product follows the design principles of simplicity, function orientation and moderate sense of technology, enabling users to intuitively understand the functional composition and usage of the product, thus reducing the learning cost and improving the interaction efficiency.

4.2. Sketch deduction

In the product scheme conception stage, this research puts forward two different design schemes around key issues such as the wearing method of haptic actuators, the degree of structural integration and the user's operational freedom. As shown in Figure 4, Scheme 1 adopts an integral glove structure, integrating the haptic module and the control system into the glove as a whole; Scheme 2 adopts a split-type structure combining a finger cot-type haptic module with a dorsal hand control unit, realizing haptic feedback functions through partial wearing.



Option 1

Option 2

Figure 4. Sketch schemes

Through a comprehensive comparison of the two schemes in terms of wearing experience, structural complexity and product scalability, this research finally selects Scheme 2 as the main product design direction. Compared with the integral glove scheme, Scheme 2 has a more concise structure. The haptic module is directly fixed on the key haptic areas of the fingertips in the form of finger cots, reducing the restriction of the overall covering structure on the natural movements of the hand. At the same time, this scheme avoids the problems of size adaptation, stuffiness and wearing complexity that may be brought by the full glove structure, and is more conducive to users' quick wearing and adjustment. It emphasizes the characteristics of a modular, detachable and lightweight haptic interaction product. The fingertip haptic modules can be selectively worn on specific fingers according to interaction needs to realize the combined output of different haptic information; the dorsal hand area integrates the control circuit and power supply module as the core control unit of the system, which is connected with each fingertip module through flexible circuits, thus maintaining the flexibility of the overall structure while ensuring the realization of functions.

4.3. Product appearance and structure

After clarifying that the product adopts the design direction of a split-type and modular haptic interaction scheme, this section carries out specific design explanations around the overall appearance form and structural composition of the haptic interaction glove.

4.3.1. Overall appearance form design

Compared with the integral glove structure, the scheme adopted in this research presents the design characteristics of lightweight and split-type in the overall appearance. As shown in Figure 5, the product consists of three parts: fingertip haptic modules, a dorsal hand control module and a flexible connection structure. The overall visual form is more concise, reducing the restriction of large-area covering structure on the free movement of the hand.

Figure 5. Overall effect

4.3.2. Modular design of fingertip haptic modules

The fingertip haptic module is the core component of the product, whose design focus is on replaceability and independence. As shown in Figure 6, each fingertip module exists as an independent unit, connected to the dorsal hand control module through a flexible connecting line, and is structurally independent of other fingertip modules. In terms of structural design, the fingertip haptic module adopts a compact finger cot structure, which can be directly fixed on the key haptic perception areas at the fingertips. This structure can ensure that the haptic actuator is stably attached to the skin. At the same time, the finger cot structure provides necessary support and protection for the haptic module without affecting the flexion and extension of the fingers.

a. Finger cot

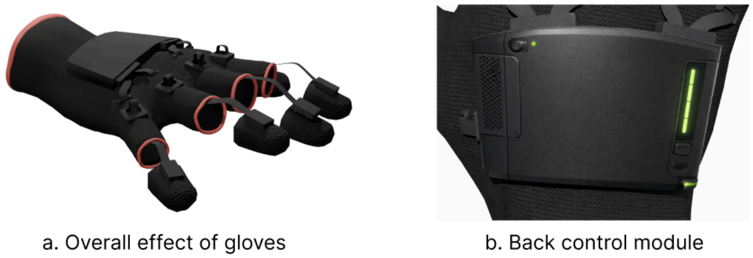
b. Internal finger cots

Figure 6. Finger cot details

4.3.3. Dorsal hand control module

As shown in Figure 7, the dorsal hand control module, as the core control unit of the entire haptic interaction system, integrates a circuit board, a communication module and a power supply interface. The module is arranged on the dorsal hand area, on the one hand, utilizing the characteristics of this area with relatively stable position and small movement range to reduce the impact of module shaking on the use experience; on the other hand, avoiding arranging heavy electronic components on the fingertips or palm area, thus reducing the wearing burden. The dorsal hand module is connected to the hand through a fixed structure and a strap system, which can be adjusted according to different hand shapes to ensure wearing stability. The fingertip haptic modules are connected to the dorsal hand module through flexible circuits, which are arranged along the natural direction of the dorsal hand to avoid pulling or restraining the finger movements as much as possible.

The split-type structural design makes the system highly flexible on the whole. Users can choose to wear some or all of the fingertip modules according to actual needs to achieve different levels of haptic interaction experience. This structural form is especially suitable for haptic application scenarios in virtual reality that focus on prompt and guidance.


a. Overall effect of gloves

b. Back control module

Figure 7. Overall effect of the glove and dorsal hand control module

5. Conclusion

With the continuous expansion of virtual reality technology in fields such as entertainment experience, education and training, and simulation training, users' requirements for immersive interactive experience have gradually shifted from a single visual and auditory perception to a more real and multi-modal information feedback form. However, the current mainstream VR systems still mainly rely on visual and sound prompts in the interaction process, lacking haptic feedback corresponding to virtual operation behaviors, which makes it difficult for users to obtain real interaction confirmation when touching, grasping and operating virtual objects, thus affecting the immersion and operational reliability to a certain extent.

To address the above problems, this paper carries out a systematic research on virtual reality haptic interaction products from the perspective of product design. By sorting out the composition of the virtual reality interaction system and the development status of haptic interaction technology, it analyzes the deficiencies of existing VR haptic interaction products in terms of wearing comfort, interaction naturalness and structural integration; secondly, it obtains users' interaction pain points and haptic demand preferences in the process of virtual reality experience based on the questionnaire survey method.

On this basis, this paper further converts user needs into haptic interaction information requirements. Combined with the results of demand analysis, this paper proposes a design scheme of a split-type haptic interaction product combining a fingertip haptic module with a dorsal hand control unit. Adopting a modular design idea, the scheme uses finger cot-type haptic units to act on the key haptic areas at the fingertips, reducing the restriction of the full hand covering structure on the freedom of hand movements while ensuring the perceptibility of haptic feedback; the dorsal hand control module is used to integrate the control circuit and power supply system, thus achieving a balance between function realization and wearing comfort.

The research results show that the user demand-oriented modular haptic interaction product design method can improve the operation confirmation efficiency and situational feedback capability in the virtual reality interaction process to a certain extent, and provide a reference path for the lightweight and product-oriented design of virtual reality haptic interaction products.

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Appendix: questionnaire results

Table A1. Statistical results of the questionnaire survey

Category		Subcategory	Number of People
Gender	Male	34	57.14%
	Female	26	42.86%

Table A1. Continued

Age	Under 18	6	10.71%
	18-22 years old	49	82.14%
	23-26 years old	5	7.14%
	27-30 years old	0	0%
	Over 30	0	0%
Have you experienced VR devices?	Yes	34	57.14%
	No	26	42.86%
Frequency of VR use	Never	25	42.86%
	Occasionally	35	53.57%
	1-3 times a month	2	3.57%
	Once a week or more	0	0%
Types of experienced VR content	Gaming & Entertainment	38	64.29%
	Fitness & Exercise	8	14.29%
	Immersive Viewing/Exhibitions	32	53.57%
	Education & Training	2	3.57%
	Virtual Tourism/Exploration	19	32.14%
	Social Interaction	9	14.29%
Used VR interaction methods	Controller	41	67.86%
	Gesture Recognition	11	17.86%
	Motion/Full-body Tracking	30	50%
	Voice Control	13	21.43%
Difficulty in directional sense or spatial positioning frequently occurs in VR	1	24	39.29%
	2	11	17.86%
	3	21	35.71%
	4	2	3.57%
	5	2	3.57%

Table A1. Continued

Frequently rely on UI prompts	1	17	28.57%
	2	9	14.29%
	3	19	32.14%
	4	13	21.43%
	5	2	3.57%
Uncertain whether one's operation is activated successfully	1	15	25%
	2	13	21.43%
	3	21	35.71%
	4	6	10.71%
	5	4	7.14%
UI visuals distract attention and affect immersion(Rating)	1	13	21.43%
	2	11	17.86%
	3	26	42.86%
	4	11	17.86%
	5	0	0%
Reliance solely on voice prompts is not entirely clear and reliable(Rating)	1	15	25%
	2	11	17.86%
	3	24	39.29%
	4	9	14.29%
	5	2	3.57%
Is adding haptic feedback in VR helpful?	Very useless	4	7.14%
	Useless	4	7.14%
	Average	15	25%
	Useful	21	35.71%
	Very useful	15	25%

Table A1. Continued

In which scenarios do you most hope haptic feedback appears?	Confirmation feedback when touching/grabbing objects	36	60.71%
	Confirmation feedback for button/switch operations	41	67.86%
	Event prompts such as impact/collision	39	64.29%
	Path navigation/directional prompts (left/right/forward/stop)	21	35.71%
	Prompt when approaching key targets/interaction points	9	14.29%
	Task completion/progress reminder	9	14.29%
Which parts of the hand do you prefer haptic feedback to act on?	Fingertips	36	60.71%
	Finger pads	32	53.57%
	Palm	39	64.29%
	Back of the hand	24	39.29%
	Wrist	15	25%
	Forearm	19	32.14%
Which method do you prefer for "directional prompts"?	Visual arrows/pop-ups	28	46.43%
	Voice prompts	21	35.71%
	3D sound direction (sound localization)	32	53.57%
	Haptic prompts (different fingers/rhythms)	17	28.57%
	Combination of visual and haptic	6	10.71%
Is it easy to understand that "different finger vibration combinations represent directions/instructions"?	Very difficult to understand	6	10.71%
	Relatively difficult	15	25%
	Average	21	35.71%
	Relatively easy	11	17.86%
	Very easy	34	10.71%

Table A1. Continued

Which haptic intensity are you more willing to accept?	Very slight (almost imperceptible)	6	10.71%
	Slight but perceptible	11	17.86%
	Moderately obvious	34	57.14%
	Obvious and intense	9	14.29%
	Adjustable (varying intensity in different scenarios)	0	0%
If tactile cues are too frequent, I feel distracted or fatigued.	1	13	21.43%
	2	6	10.71%
	3	24	39.29%
	4	13	21.43%
	5	4	7.14%
Which wearing style do you prefer	Full glove style (covering palm/back of hand/fingers)	13	21.43%
	Fingertip cover modular style (tactile modules worn only on fingertips)	32	53.57%
	Wristband/bracelet style	11	17.86%
	No wearing (handle vibration only)	4	7.14%
Your acceptance of "replaceable/detachable fingertip tactile modules"	Completely unnecessary	6	10.71%
	Not very necessary	6	10.71%
	Neutral	30	50%
	Necessary	15	25%
	Highly necessary	2	3.57%
What is the greatest value of replaceable fingertip modules to you?	Can be replaced individually when damaged for easy maintenance	24	39.29%
	Can change different modules for different scenarios (intensity/mode)	17	28.57%
	Only install modules for needed fingers for lighter wearing	32	53.57%
	Facilitates upgrading and iteration	9	14.29%

Table A1. Continued

What is your biggest concern when wearing tactile devices?	Weight	24	39.29%
	Breathability/Stuffiness	28	46.43%
	Restriction of movement/Impairment of actions	39	64.29%
	Cable interference	11	17.86%
	Complicated wearing process	21	35.71%
	Safety (electricity/heat)	13	21.43%
	Obvious/unattractive appearance	9	14.29%
	Price	6	10.71%
Continuous wearing duration you can accept	Within 10 minutes	6	10.71%
	10–20 minutes	15	25%
	20–40 minutes	19	32.14%
	40–60 minutes	15	25%
	Over 60 minutes	5	7.14%
Are you willing to pay for a "tactile interaction device that significantly enhances immersion"?	Unwilling	15	25%
	It depends	28	46.43%
	Willing	17	28.57%
Acceptable price range	Below 200 yuan	30	50%
	200–500 yuan	23	37.5%
	500–1,000 yuan	0	0%
	Above 1,000 yuan	7	12.5%