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REVIEW PAPER

Research and prospects of virtual reality systems applying exoskeleton technology

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Abstract
As a typical application of human–machine fusion intelligence, the exoskeleton is an indispensable intelligent interaction device for virtual reality. At present, there are an increasing number of studies on virtual reality systems using exoskeleton technology, especially in the field of medical rehabilitation. In this paper, for the first time, a virtual reality system with the application of exoskeleton technology is considered as the research object. We refer to three key human–machine interaction processes: recognition, perception, and feedback. The virtual reality system that uses exoskeleton technology is divided into positioning technology, multisensory interaction, and feedback technology. First, this study conducts literature research and then summarizes the technical characteristics, system architecture, and research status for key content such as positioning technology, multisensory interaction, and feedback technology. Finally, the three research aspects of the virtual reality system applying exoskeleton technology are summarized, considered, and prospected.

Keywords Virtual reality · Exoskeleton · Positioning technology · Multisensory interaction · Feedback technology

1 Introduction

Virtual reality (VR) was first proposed in 1989 by the company VPL Research in the USA. It primarily describes the integration of computer simulation technology [1] with several technologies, such as multimedia technology, sensing technology, and human–machine interface, and it is applied to the research of cross-cutting frontier technologies and disciplines. VR technology is widely used in entertainment and simulation training. Furthermore, VR technology has a wide range of applications and is valued by research in various disciplines as well as generally accepted by society [2–6].

VR is a reality imitation application system with 3I characteristics (immersion, interaction, and imagination). The technology of VR systems includes environment simulation, multidimensional interaction, and feedback devices. Environment simulation generates a real-time dynamic simulation environment through parameter modeling of the virtual environment and three-dimensional objects. Then, the dynamic objects are identified and located, superimposed on the virtual environment to achieve a combination of virtual and reality environment simulation. Multidimensional interaction is based on the visual environment generated by computer graphics, combined with auditory, haptic, olfactory stimuli, and gustatory, to bring a stronger sense of immersion. Feedback devices are external interaction devices for VR technology that can realize the collection and feedback of human data. These include collecting body data, action behavior, user intention, etc., and provide corresponding feedback after a judgment. At the same time, the operation of external devices can also be mapped to the virtual environment, thereby changing the corresponding parameters in the virtual environment and finally constituting a more diversified multifunctional system.

As a smart device in future society, exoskeletons will play an important role in enhancing the experience of VR. The exoskeleton robot is a wearable mechanical device developed by imitating a human exoskeleton. The exoskeleton combines the intelligence of humans and the physical strength of robots by integrating information perception,

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information fusion, and intelligent control technologies [7]. Adding to the intelligence of human control, the robot provides strength support, motion assistance, and other functions. As a bio-mechatronic device to enhance human functions, the development of exoskeletons requires knowledge of various disciplines, such as mechanics, electronics, automatic control, computer science, biomechanics, ergonomics, and industrial design; thus, they have high development difficulty and research value. At present, exoskeleton robots are mainly used in military combat assistance handling, industrial intellectual manufacturing of high-intensity operations, medical rehabilitation treatment, travel assistance, etc. [8–10]. The synergistic research of exoskeletons and VR has emerged in recent years. With the help of exoskeleton devices, people can realize comprehensive communication with the virtual environment and have the ability to transmit information in both directions [11]. The integration of exoskeletons and software media is a new research trend and popular configuration.

To explore the synergistic mode of the exoskeleton and VR, this study divides the exoskeleton and VR into three combination modes based on human–machine–environment cooperation and the method of wearing by users. We also integrate the model specifications of the two technologies to create an intelligent ecology of human-cyber-physical systems. Figure 1 shows the three modes of synergy. In Mode 1, the exoskeleton is worn on the human body and operated accordingly. The exoskeleton provides the acquisition and feedback functions. VR presents a multisensory interaction. The exoskeleton is in direct contact with the user and can realize the auxiliary functions of drive, impedance, support, load, etc. In related studies, Wei [12] designed a lower limb exoskeleton robot that uses VR hardware to capture the user's behavior and transmit it to VR for replication. The behavior is then modified in the real world, resulting in a closed-loop immersive rehabilitation experience. Moreover, Gancet et al. [13] led a project MINDWALKER, which is mainly the development and integration of Brain Neural Computer Interfaces (BNCI), exoskeleton, and VR three technologies. This project culminated in the demonstration of a prototype BNCI-controlled lower extremity exoskeleton combined with a VR training environment to empower spinal cord injured patients with walking ability. In Mode 2, the exoskeleton is not worn on the body but is remotely controlled by the user to manipulate the behavioral actions of the exoskeleton. VR also provides sensory interactions. The exoskeleton does not have direct contact with the user and will support, load, carry, and perform other movement behaviors for the target objects commanded by the user. Ferrero et al. [14] found that during the VR training phase, subjects could focus on Motor imagery (MI) and avoid distractions. That helps subjects create a robust brain–computer interface classifier model that would be used later to control the exoskeleton. Meanwhile, the noninvasive BNCI method based on functional magnetic resonance imaging has been shown by Honda firm to provide reasonable control of Asimo's motion [15]. That would also help to propose an intelligent machine space for human robot interaction. Lee et al. [16] combined VR to communicate the current state of the robot itself bidirectional way. In Mode 3, the exoskeleton

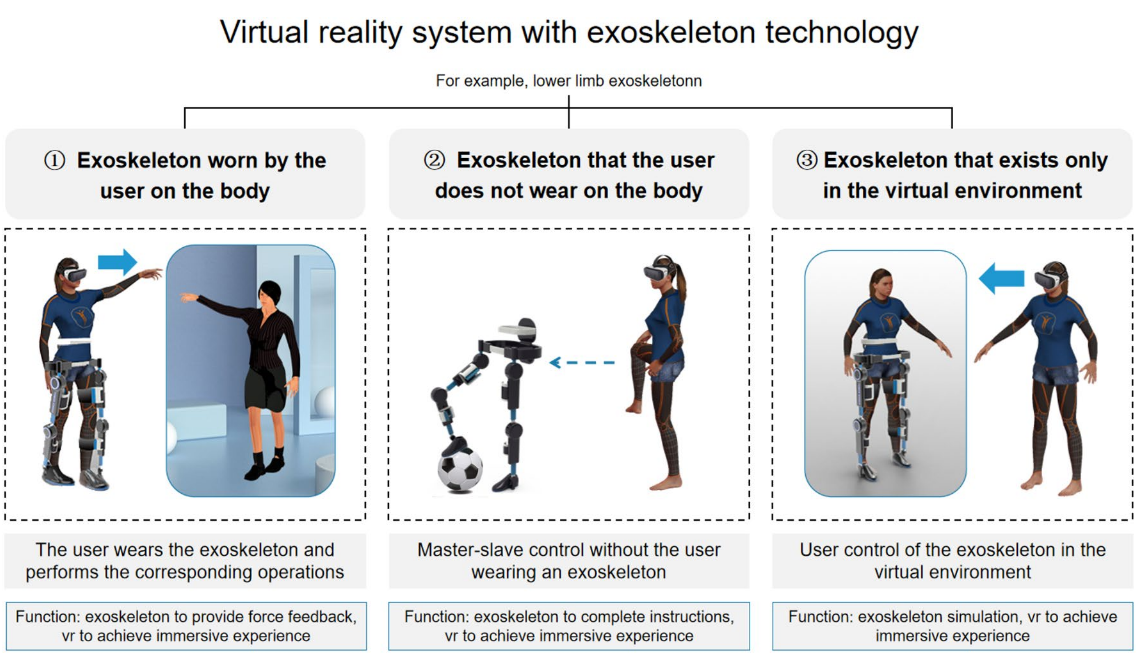

Fig. 1 Synergistic mode of the exoskeleton and VR systems

exists only in a virtual environment. In the virtual space, the exoskeleton shape, color, and material are simulated, and multisensory interactions, such as vision, audio, and touch, can be provided to the user. The environmental simulation of the exoskeleton is provided to the user to simulate the specified scenarios and behavioral actions of the exoskeleton and the user operation. Gancet et al. [17] presented a VR training environment for human upper body tracking. The kinematic exoskeleton is the output of the Kinect tracking system and is connected to the virtual human body via several 6 DOF Cartesian couplings. Both virtual exoskeleton models and virtual human models are robot-like models. Soleimani Amiri et al. [18] simulated a human exoskeleton in a virtual environment to simulate the interaction between the exoskeleton and the patient. This paper divides the system into three categories, characterizes and standardizes the human–machine–environment synergy mode, clarifies the composition and mode of the VR system applying exoskeleton technology, and provides ideas for more extensive and in-depth system research.

Since the current research, literature and review articles for exoskeleton and VR systems are basically organized in terms of fields. The lack of a systematic perspective on the combing of related technologies makes the research on the systems across fields have high barriers and do not have widespread reference value. In addition, the failure to integrate the mode specifications of the two technologies and the lack of human-centered core logic lead to the current system still failing to show a clear and comprehensive research structure. With the above research questions, it is imperative to explore the system architecture and key technologies of exoskeleton and VR systems from a new viewpoint. Consequently, Fig. 2 shows the organization of the study structure to completely define the research of the VR system with an exoskeleton. According to the three processes of recognition, perception, and feedback of human–machine interaction, this study divides the research content into positioning technology, multisensory interaction, and feedback technology. The research mechanism of the system is that after the machine recognizes the target object, it can provide the user with multidimensional perception and bidirectional feedback dialogue, thus generating a realistic immersion and providing powerful functionality. The key process also corresponds to the three research aspects of exploring positioning technology, multisensory interaction, and feedback technology. This comprehensively outlines the main architecture of the system and regulates the key technologies of the research, thus further exploring the technical characteristics, application value, and other specific content. It helps to clarify the direction and innovative functions so that the VR system applying the exoskeleton can be widely used in richer user scenarios and address user needs and problems.

The remainder of this paper is organized as follows. Next, a literature research and author collaborative analysis through literature retrieval and screening is conducted, and the limitations and deficiencies of current research are summarized based on specific cases. Chapter 3 of this paper classifies and compares positioning technology. We discuss

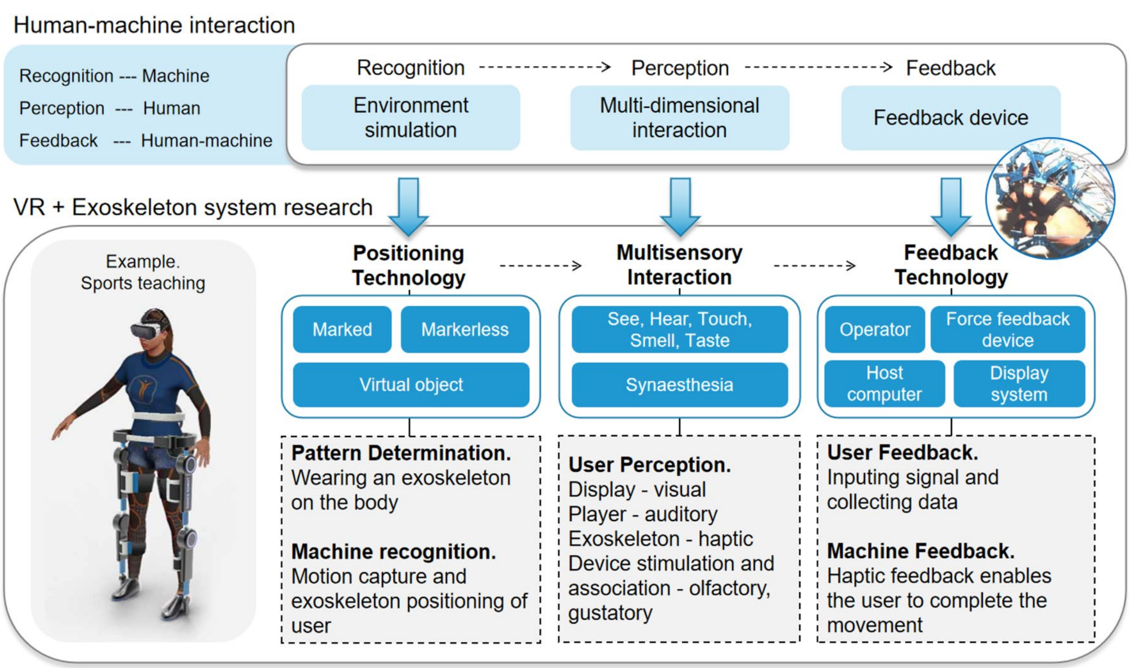

Fig. 2 Structure of the system research

the research status and introduce technical principles, technical characteristics, application scenarios, and specific research results to discuss the development direction of exoskeletons in VR positioning technology. In Chapter 4, after discussing the theory of perception for multisensory interaction, we describe the system architecture of various sensory interactions through literature sorting and analysis. Furthermore, we showed the interaction mode and architecture of multisensory information in VR, and conducted a literature analysis to obtain some conclusions. In Chapter 5, we focus on feedback technology, summarize the composition of the force feedback technology, and conduct research and discussion. Finally, we summarize the above research content and look ahead to the integration and development directions of the two technologies of exoskeleton and VR.

2 Related work

Through keyword search, citation search, and literature screening on the Web of Science repository [19], this study collected 189 research papers on the topic of VR and exoskeleton technology published over the past 20 years. The search was conducted for studies on the topics searching for exoskeletons and virtual reality (or VR) as keywords, with publication years between 2000 and March 2021. The document types were papers and meetings, excluding books, letters, case reports, and other forms of publications. For further analysis, Fig. 3 presents the publication year, research area classification, and authors' co-authorship network of the retrieved research papers. Figure 3a shows the year distribution of published literature, which shows that the number of studies in this research direction shows an obvious upward trend and has reached a relatively stable number of studies in the past five years. Figure 3b illustrates the general distribution of the basic classification and research directions in the literature. It can be seen that VR and exoskeleton technology are mostly researched in the field of science and technology. Among them, the most prominent fields are computer science, engineering, robotics, and automation control systems. But fewer studies have been conducted in the areas of physical sciences and arts humanities. Only a few studies have been published in the direction of educational research, physiology, and cardiovascular system cardiology. Therefore, there will be a large research potential in the future. To understand the collaboration between authors and the scale of research in this field, we use social network analysis [20] to analyze the authors' co-authorship network of the collected literature. Figure 3c shows the visualization results of the authors' co-authorship network obtained using Gephi network software [21], in which 696 network nodes representing authors, 1,512 edges representing author collaborations, and 161 connectivity subnetworks are shown. The visualization of the network statistics shows that many research teams that have conducted relevant explorations are relatively independent, with fragmented collaborations. This is related to the fact that this research field is still in an emerging stage and to the characteristics of diversified application scenarios. Figure 3d shows a list of the most prominent authors in the collaborative network. Among them, Antonio Frisoli's team is relatively prominent and has published 14 relevant articles, mainly investigating the exoskeleton robot rehabilitation system in a virtual environment applied to the field of clinical medicine. Based on the organization and analysis of the above authors' co-authored articles, it can be seen that the research teams in this field are scattered but are beginning to take shape.

It can be seen from the literature that research has advanced in recent years. Wei [22] studied an exoskeleton robot-assisted training system based on VR to rehabilitate patients with neurocentral nerve injury and used an upper-limb rehabilitation robot with a virtual training game to achieve rehabilitation treatment for hemiplegic patients. Zhang [23] designed and implemented an exoskeleton mechanical structure according to the physical and psychological characteristics of children and combined it with VR technology to realize an interaction between the exoskeleton and the game scene. Karvouniari et al. [24] proposed a VR-based integrated decision-making tool for exoskeletons in industrial production lines to fine-tune the elements of exoskeletons based on simulation results and to train workers to use different exoskeletons effectively, correctly, and safely. Secco and Tadesse [25] presented a two-finger exoskeleton interaction in VR. Their exoskeleton optimized performance in terms of low weight and good adaptability, and this design also made the exoskeleton easily wearable and allowed strong force feedback to manipulate the real motion of objects in VR. In their summary, Mubin et al. [26] classified these studies according to the relevant technologies used and detailed the studies for upper and lower extremity applications. The analysis of randomized controlled trials and exploratory studies demonstrated the effectiveness of exoskeleton robots with VR, augmented reality (AR), or gamification in improving the activity and participation of post-stroke survivors. Jiang et al. [27] presented the working principles and research applications of parabolic flight, VR technology, and passive exoskeleton systems for low-gravity environment simulation methods applied to astronaut training. Furthermore, they provided a comparative analysis of the advantages and disadvantages of these methods. Zhang and Ren [28] summarized the positioning technology of VR, introduced mainstream positioning devices and the corresponding positioning algorithms, and discussed the current technical problems and future development directions. The above domestic and foreign literature and

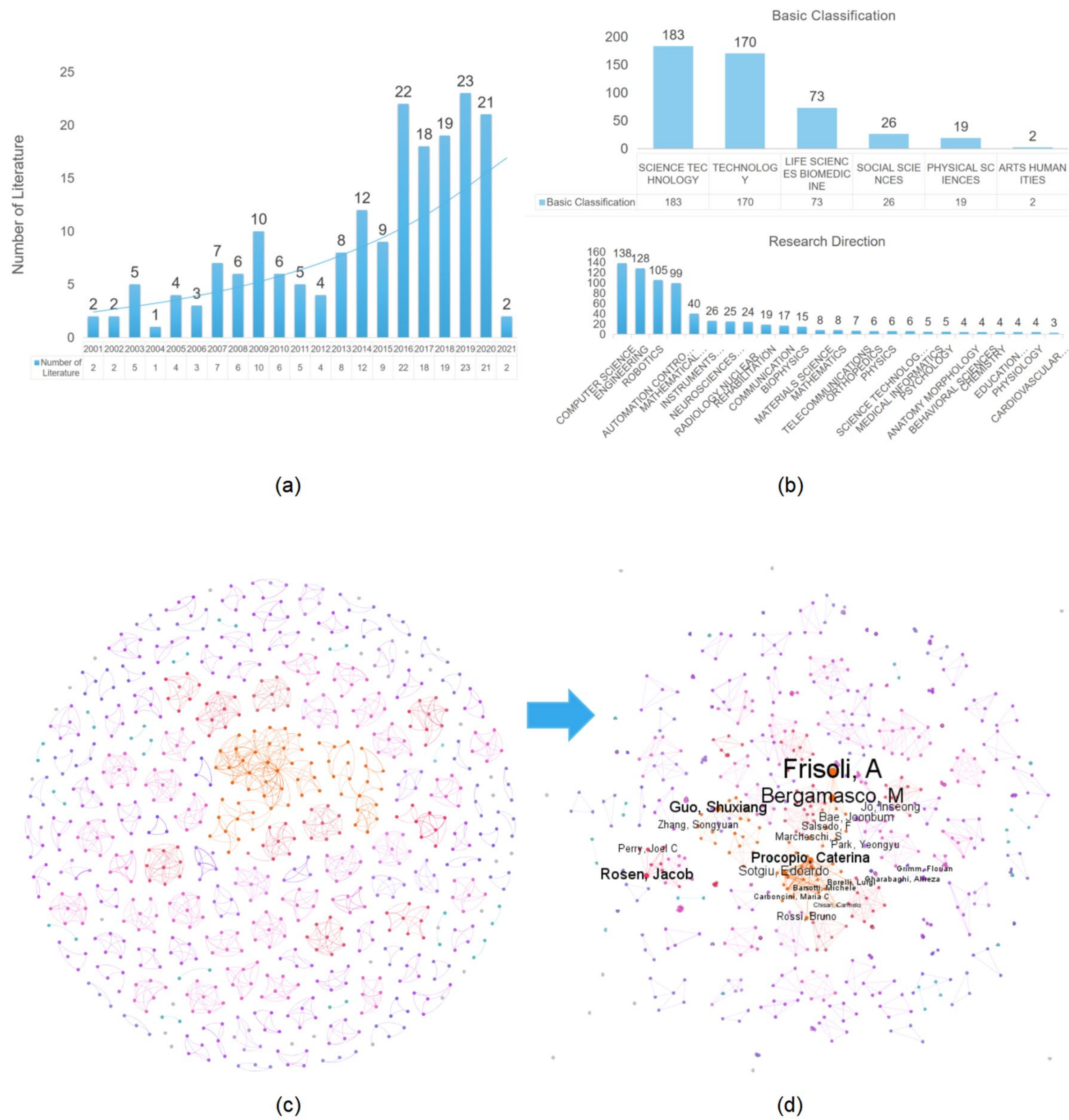

Fig. 3 Literature research and author collaborative network

review articles only provided an overview of research under a certain application area or specific issues, such as positioning technology, and did not provide a systematic summary, generalization, and outlook for the combination mode of the two technologies. The above statistical results based on Gephi software show that the research teams in this field are not concentrated, and the research is distributed over various application fields and functional structures. Thus, the literature summary is not focused and complete and lacks the combination of key technologies and configuration modes for the research of VR and exoskeleton systems. The current research on systems combining exoskeleton and virtual reality technologies still fails to present comprehensiveness and generality, and cannot widely provide technical references for researchers in various fields.

3 Positioning technology

In the VR system, the identification and positioning of the target is the core foundation for ensuring a connection between the virtual and real environments. According to the collaborative model of the system, the positioning technologies corresponding to the three modes can be classified into marked positioning, which the user wears on the body, unmarked positioning, which the user does not wear on the body, and virtual positioning, which only exists in the virtual space. By summarizing and organizing the positioning technologies, we introduce the technical principles, technical characteristics, application scenarios, and specific research results, and discuss the development direction of exoskeletons using VR positioning technology.

3.1 Marked positioning technology

Currently, the following marking positioning technologies are available: infrared, laser, visible light, ultrasonic, Bluetooth, and Wi-Fi. All of these are commonly used for target positioning in indoor spaces [29]. However, the positioning of the exoskeleton usually needs to be accurate for the recognition of postural movements to achieve tracking and interaction between human and mechanical devices, which has a significant impact on research in many fields such as teaching and training, medical rehabilitation, and industrial manufacturing. As shown in Table 1, different positioning technologies are compared to explore the principles and characteristics of positioning technology and to delineate the positioning technology suitable for capturing exoskeleton movements. As can be seen from Table 1, optical motion capture has higher accuracy compared to inertial motion capture, while acoustic motion capture has a large latency and low accuracy, and electromagnetic motion capture devices have strict requirements for the environment. Therefore, infrared, laser, and visible light positioning technologies can best meet the exoskeleton motion capture requirements.

Infrared positioning technology Infrared is an electromagnetic wave with a wavelength between radio and visible light waves. Infrared positioning technology determines the user's position in space by arranging multiple infrared emitters in space and infrared reflection points on the target object to capture the reflected image [30]. Although infrared rays have relatively high indoor positioning accuracy, they can only propagate visually because of the inability of light to pass through obstacles. The two main drawbacks of linear line-of-sight and short transmission distance make them unsuitable for indoor positioning. Therefore, infrared rays are only suitable for short-distance propagation and are easily interfered with by fluorescent lamps or lights in the room, which has limitations in precise positioning.

In terms of the representative OptiTrack positioning scheme [31], the basic principle is to use multiple infrared emitting cameras to cover the indoor positioning space, to place infrared-reflective points on the tracked objects, and to determine the location information of the objects in space by capturing the images reflected by the camera from these reflective points. Kilteni et al. [32] conducted a hand drumming experiment, in which participants were asked to wear an OptiTrack Motion Capture suit to achieve body motion capture with 34 attached markers, while wearing a stereo NVIS nVisor SX111 head-mounted display (HMD). Furthermore, an OptiTrack Arena whole-body motion capture software was used to capture and stream the motion data. The laboratory camera operated with sub-millimeter accuracy and "very good" calibration quality, accurately locating the real-world drum position to coincide with the virtual drum position, and calibrating the avatar's position on the vertical axis to align the subject's virtual hand tracking position with the surface of the virtual drum. OptiTrack can achieve very high precision positioning but is expensive, and will be primarily used in the direction of animation production, film, TV shooting, etc.

Laser positioning technology Laser positioning uses the laser signal, calculates the distance between the signals reflecting from the object based on the time difference. The angle of the emitted laser is used to determine the angle between the object and the emitter and to derive the relative

Table 1 Virtual reality positioning technology comparison

Technology	Positioning principle	Ease of deployment	Cost	Environmental dependency	Ease of motion capture
Infrared	Geometric feature	Difficult	High	High	Easy
Laser	Laser scanning	Difficult	Very high	High	Easy
Visible light	Location algorithm	Easy	Low	General	Easy
Computer vision	Pattern recognition	Easy	Low	Low	Easy
Ultrasound	Trilateral positioning method	Easy	General	General	Somewhat difficult
Bluetooth	Location algorithm	Difficult	High	High	Difficult
Wi-Fi	Fingerprint location algorithm	Easy	Low	High	Difficult
Inertial sensor	Algebraic integration	Easy	Low	Low	Difficult
Radio Frequency Identification	Proximity information	Difficult	General	High	Somewhat difficult
Electromagnetic	Location algorithm	Difficult	High	High	Somewhat difficult

position of the object and the emitter. The distance between the laser and each reflector can be calculated in the process of laser scanning for a cycle, and the distance between any two reflectors can be calculated using the trigonometric formula according to the sensing time and sweeping period. The measured distance can be compared with the offline theoretical value to match the number and position information of each reflector [33]. Laser positioning is primarily applied indoors and requires the installation of a certain number of reflective panels, which requires attention to the accuracy of the installation, the distance between the panels, avoiding windows during installation, and asymmetric arrangement. The advantages of this positioning system are lower cost compared with the expensive infrared motion capture camera; the use of a laser light tower for motion capture cost is relatively low. Moreover, high positioning accuracy can achieve excellent immersion, providing the user with a sense of shock.

HTC VIVE [34], for example, uses a positioning system called Lighthouse, which consists of two base stations. Each base station includes an infrared LED array and two infrared laser emitters with rotating axes perpendicular to each other. The rotation speed is 10 ms per revolution. The base stations operate in a 20 ms cycle, with the IR LEDs flashing at the beginning of the cycle, the X-axis rotating laser sweeps through the entire space in 10 ms, while the Y-axis does not emit light. The Y-axis rotating laser sweeps through the entire space in the next 10 ms, while the X-axis does not emit light. Lighthouse base station Valve under the high-speed camera installed many light-sensitive sensors on the HMD and controller. After synchronizing the signal with the LED flash, the time when the X-axis and Y-axis lasers arrive at the sensor can be measured; thus, the X-axis and Y-axis angles of the sensor relative to the base station can be calculated. The positions of the photosensitive sensors distributed on the HMD and controller are also known. Therefore, the position and motion trajectory of the HMD can be calculated using the position difference of each sensor. Spitzley and Karduna [35] verified the kinematic data collection capability of an HTC VIVE VR system by evaluating the accuracy of its system. The data showed that the HTC VIVE VR system has the potential to be an effective and reliable means of kinematic data collection. However, further research is needed to determine whether it is suitable for capturing very small or large volumes of motion. HTC VIVE, owing to its required Lighthouse, has created the best VR experience because of its small computing power, low latency, and other advantages.

Visible light positioning technology Visible light positioning is an emerging field of research. Its positioning principle is to complete the positioning of calibration points by coding each LED light, using an LED array whose position is known as a reference point, modulating the ID on the light and emitting light signals while lighting. Then, a camera is used to identify these codes and determine the corresponding position in the map database through the acquired information. Visible light communication allows the user location information to be transmitted through the lighting facilities. The advantages of visible light positioning technology include a large dynamic range, high-speed communication, and relatively low cost; however, the accuracy is relatively low, and the influence of natural light is relatively large. The characteristic of distinguishing different positioning points with different colors limits the number of trackable points. However, its algorithm is simple, inexpensive, and easily scalable, which makes it a relatively popular positioning solution on the VR market today.

LEDs are very suitable for transmitting data signals owing to their high brightness, affordability, low power consumption, and minimal heat generation. Moreover, LEDs can be modulated at relatively high rates. Lou et al. [36] studied the application of LED-ID technology to provide variable location information for indoor positioning systems. Huang and Zhang [37] introduced an indoor positioning system based on dim light VLC, which can effectively avoid energy waste. It was tested and evaluated in a laboratory-view environment with real system parameters. In VR applications, the Sony PlayStaTIon VR [38] device uses a body camera and PS MOVE light-emitting sphere to locate the human head and its activity in 3D space. The PS camera and PS MOVE handle must be used in conjunction with the PlayStaTIon VR HMD, and the PS MOVE handle is installed with light-emitting spheres. Each handle and the HMD deploy a light source. The LED light ball can be self-luminous, and different light ball luminous colors, so the location between the light ball and background can be distinguished well. However, the disadvantage of the PS system is that when the users block each other, the positioning will be affected. The effective range of a binocular camera is relatively small; therefore, it is only suitable for sitting in front of the PC. Because of the nature of visible light technology, it is easily affected by the external environment, background color, etc., which are the primary problems that need to be solved.

3.2 Markerless positioning technology

Markerless positioning is a method of motion tracking that avoids the use of markers and does not require a specially prepared environment, making it flexible and efficient. A camera is usually placed in the HMD to help the system determine the location of the target. It can be used for human–machine positioning when the user is not wearing an exoskeleton and the exoskeleton is remotely controlled and command-driven, such as in simulated rescue, military combat, and other application scenarios.

Markerless three-dimensional target positioning belongs to the field of computer vision; the image captured by the camera is segmented and the feature template of the target object is established. The features of the target object are used to identify and calculate the target object relative to the camera's three-dimensional information. Finally, the target object can be superimposed on the virtual environment items in the real space of the three-dimensional coordinate system through the graphics engine. Currently, the camera's built-in HMD simplifies the setting of the VR experience environment to meet the premise of markerless 3D positioning and is not constrained by a specific space, allowing the user greater freedom of movement. Although marker-based systems perform better in terms of accuracy and latency, markerless positioning technology is also attractive and has more research and applications in both Augmented Reality(AR) and VR.

In AR research, markerless positioning technology has more extensive R &D and applications. Lange et al. [39] developed open-source middleware to provide sample applications based on sensor-based technology as an augmented interaction with game-based training/rehabilitation tools in virtual environments. With Prime Sense, Kinect sensors, and open-source middleware, markerless whole-body positioning can be provided on a conventional PC. Gao et al. [40] proposed a new method to improve the stability and accuracy of markerless positioning in AR. Based on the visualization real-time positioning and mapping (V-SLAM) framework, the researchers added a 3D dense cloud processing step to the state-of-the-art ORB-SLAM, which mainly deals with point cloud fusion and object recognition. Experiments demonstrate that the method not only accelerates camera tracking using standard SLAM systems but also effectively identifies objects and improves the stability of markerless AR applications.

In VR research, markerless technology is more complex than technology that uses markers. If there are no markers, users can easily use rooms that are not tied to a marker already created in the application [41]. Vision-based positioning technology has gradually matured with computer graphics and computer vision to obtain registration information through image analysis, which can be used to solve the registration problem in AR to ensure that it is accurate, robust, and in real time. Hirschmanner et al. [42] introduced an intuitive VR-based humanoid robot teleoperated system that mimics the user's pose and enables the user to control the robot's arms and head. The user can obtain the robot image and control the robot's head through a VR HMD. Meanwhile, a Leap Motion Controller was used to track the user's arm motion and drive the robot's arm without the use of markers. Bicho et al. [43] proposed a markerless multi-viewpoint-based VR/AR/MR multipurpose head positioning system, which, through a combination of a Kalman filter and particle filter, achieved markerless positioning, thus reducing the computational burden of each processing module. In the field of VR, users usually interact with the virtual world through their movements. The point of view of the user's HMD is based on the user's head posture. Most systems track the user's head based on the positioning of the HMD and are usually constrained to a single user. Therefore, for the recognition of the exoskeleton, the positioning method can be applied to locate the position of the user, exoskeleton, and virtual objects. The user signal can control the exoskeleton to complete related instructions and realize master-slave control of human–machine interaction in VR.

3.3 Virtual object positioning technology

The positioning of objects in the virtual world is obtained using analog computation. The modeled objects are superimposed into the virtual environment using a 3D engine, importing external parameters for the model perspective matrix. The virtual objects or animations are superimposed on the real spatial 3D coordinate system in real time through the graphics engine to complete the virtual-real superimposition. The interaction between the computationally positioned virtual objects and the real objects is realized by the interaction function of the graphics engine. In a scenario where the user interacts with the exoskeleton in the virtual environment, innovative research and development for exoskeleton-assisted design, simulation education, and other scenarios can be conducted.

The exoskeleton modeling in its virtual environment needs to be based on biomechanical characteristics and parametric modeling of the mechanical, coupling, and musculoskeletal models. The mutual adjustment and integration of the three models rationalizes the basic functions and structure of virtual objects. To study the positioning technology of virtual objects, Chen [44] inferred the 3D coordinates of the real space backward through the Oculus Rift DK2 HMD to observe the position change of the virtual world, so that the user can complete the position movement of the virtual space by walking in the real world. Lee et al. [45] designed the TORC system, and the simulation of haptics presented in the system completes the visual simulation based on virtual positioning when the user holds an object in the virtual space. The thumb tip produced a position change on the surface of the controller, which controlled the visual orientation of the object around the center point between the fingers. Therefore, this technology has very basic applications for simulation in virtual environments. At the same time, with the development of VR rendering technology, the amount of data transfer required is increasing, and the real-time positioning of virtual objects needs to meet smooth High Definition effects. Albert et al. [46] explored the impact of latency on rendering in VR applications. They evaluated the detectability of visual artifacts and measured the optimal latency rate so that dynamic rendering, temporal stability, and latency tolerance could be improved.

3.4 Literature analysis

In this section, three positioning technologies divided by the exoskeleton wearing mode and interpreted in detail are presented. To explore the degree of research and applicability of each technology, we led to the following conclusions (Table 2). (1) The Web of Science search platform has WOS, DIIDW, CSCD, MEDLINE, and other databases of large-scale and significant fields. Laser positioning technology is widely studied and used because of its flexible features. (2) Markerless positioning is cited significantly, advancing the research on target positioning algorithms, in line with the characteristics of the era of high-speed development of artificial intelligence. (3) From the comprehensive consideration of technical principles, positioning accuracy, research quantity and application scope, laser, visible light, markerless, and virtual object positioning apply to such products as exoskeletons with complex structures and variable functions. In marked positioning, there is still much room for exploration of the exoskeleton for the use of laser positioning and visible light positioning, environmental configuration, and other issues.

4 Multisensory interaction

Multisensory information interaction has significant research significance for VR systems. As a typical representative of intelligent devices, exoskeletons are closely integrated with human–machine interaction [47], and can cooperate with HMDs and other products to study the interaction mode and architecture of multiple senses in VR systems. Multisensory interaction can not only build anthropomorphic emotional transfer but also enhance the immersion of users in the virtual environment while using advanced technical means to perceive and provide feedback containing multidimensional information, improve the emotional perception of users, and

Table 2 Virtual reality positioning technology comparison

Category	Literature	Technology	Basic principle	Precision	Data volume	Cited frequency	VR applicability	Exoskeleton adaptability
Marked positioning technology	[31, 32]	Infrared positioning technology	Using infrared emitters and infrared reflection points to capture reflected images	5m	5934	44,983	High	General
	[33–35]	Laser positioning	Technology using the laser signal to calculate the time difference of signal reflection and emission	cm	13,156	102,717	High	High
	[36–38]	Visible light positioning technology	Obtaining the location of the information in the map database with LED codes	cm	2556	33,119	High	High
Markerless positioning technology	[36, 40]	Markerless positioning technology	The algorithm uses HMD to achieve markerless motion tracking	cm	1247	13,519	High	High
Virtual object positioning technology	[44, 45]	Virtual object positioning technology	Obtaining object positioning in virtual environment through simulation calculation	cm	1081	6,267	High	High

help establish the emotional connection between the system and users.

4.1 Theory of perception

Perception is the result of the synergistic activity of multiple analyzers and comes from the acquisition of sensory information and its interpretation and organization in the context of inherent experience [48]. The process of perception is the process of organizing and interpreting this sensory information, first by interpreting it and then by giving it meaning. The acquisition of sensory information comes directly from the five human senses of vision, hearing, touch, smell, and taste. These senses are the most basic physiological sensations, resulting from direct stimulation of the senses, and are the basis of one's understanding of the outside world, allowing one to see, hear, touch, smell, and taste. The intermixing of multiple physical senses can influence one's experience of the environment in a way that is richer than the sum of the sensations brought about by experiencing each sense independently. In VR, we can create an immersive user experience through multisensory information interaction, resulting in high-fidelity multisensory stimulation and feedback.

Visual interaction Vision is directly communicated through light in the physical environment, and the quantity of visual information received in daily life is much greater than that of the information received by the other four senses [49]. Therefore, in a VR system, human vision can be fully utilized to create visual impact through the shape of objects, the texture of materials, and the reflection of light.

The human visual system receives and processes signals in the form of light waves, and the human eye is sensitive to a spectral range of approximately 400–700 nm and can effectively remember 6–12 colors; the human eye can still distinguish the details of the images after they are reduced by 104:1 [50]. The visual system of VR uses the tiny parallax of binocular vision to obtain depth perception, and its typical sensors are stereoscopic displays, such as HMDs, bracketed displays, and panoramic displays, which are the main components of VR systems. At the same time, for high-dynamic range (HDR) image display, neither computer nor TV monitor can provide a satisfactory experience because HDR images store luminance information far beyond the 8-bit (256) level. For a more realistic effect, immersive VR needs the ability to acquire HDR images and display them, and HDR renderers can be used in 3D scene rendering to assist virtual engine design and create applications. In the form of visual interaction, a new social interaction platform based on a collaborative virtual environment was proposed by Zhao et al. [51]. According to the platform, two children are allowed to play a series of interactive puzzle games in a VR environment, each controlling a virtual handle (marked with a red square) to move virtual objects that are tracked in real time using a camera. The game pages are brightly colored, and the objects are basic geometric forms, allowing for visual discrimination of object differences for user manipulation choices. Shi et al. [52] also used games to assist in the rehabilitation of patients with upper-limb motor dysfunction. The flying balloon game was designed for the training of shoulder adduction and abduction, and the visual interface uses natural simulation scenes to enable the user to integrate them more naturally. The magic ball game was primarily used for the training of upper-limb multi-joint movements, and the visual interface was a combination of 3D objects in low-purity cool colors, which is simple and clear. Therefore, the visual system in the VR system is composed of the stereo display, development tools, and form design, and Fig. 4 shows the corresponding visual system composition.

Auditory interaction Sound can provide hints or express instructions but can also adjust the ambiance and create a deeper sense of immersion. To reconstruct an auditory environment, the key lies in the eardrum of the sound wave conversion vibration. To achieve three-dimensional sound, it is necessary to determine the position of the head and shoulders as the left and right ears need to have different sound sources. The head positioning can be used to obtain the position of both ears to achieve a more realistic three-dimensional surround sound. In computer software design,

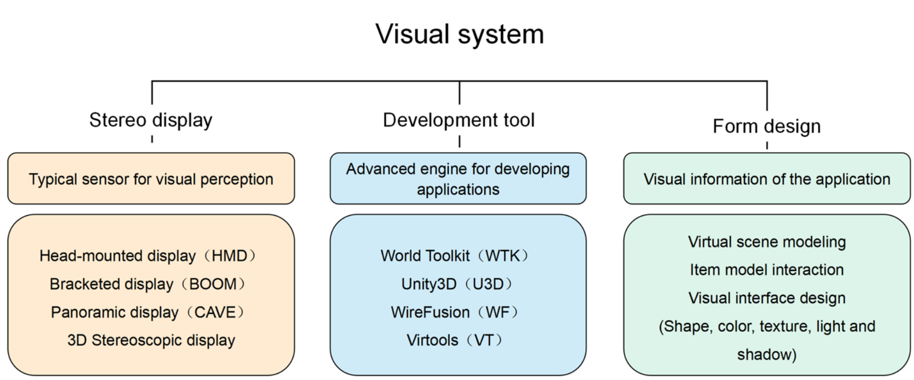

Fig. 4 Framework of visual system composition

hearing is often used to warn and prompt and for other functional designs.

The appropriate stimulus for the human ear is 16 to 20,000 sound wave vibrations per second. In the virtual environment, to provide auditory channels to give the user a sense of immersion, VR technology requires equipment to simulate three-dimensional virtual sounds and play a three-dimensional sound. The content of the sound is designed using acoustic software to create the required included, simulated, and synthesized soundtracks. Figure 5 shows the composition of the auditory system in a virtual environment. Jiang et al. [53] developed a web-based online VR presentation tool for participatory evaluation of urban sound environments. Both synthesized and recorded sounds using the Unity engine were used and presented, and the tool was tested online, with results demonstrating the applicability of online VR to urban sound environments. In addition, the application of sound is indispensable in exoskeleton and VR systems. According to Wu et al. [54], an upper-limb body exoskeleton rehabilitation training was designed, and the training experiment consisted of a volunteer wearing an exoskeleton playing a virtual airplane game, which included visual and acoustic feedback instructions. In the training system of the exoskeleton, the sound is primarily used for background, sound effects, and instructions, and the auditory interaction can be expanded with more functions in more scenarios in the future.

Haptic interaction Receptors distributed on people's skin react to external stimuli such as temperature, humidity, pressure, vibration, etc., causing hot, cold, moist, soft, hard, pressure, pain, vibration, and other sensations [55]. Haptics in VR can help users to perceive and manipulate the virtual environment, such as the perception of heat, cold, pain, pressure, or light touch, and to interact with objects in the virtual environment.

Haptics in a VR environment is divided into two stages: first, to obtain natural human interaction, such as gestures and postures, and second, the virtual system provides feedback externally. Figure 6 shows the main haptic system composition; a haptic interaction consists of a signal input source, force feedback device, and computer system. Usually, the operator inputs a force or motion signal to the virtual environment through the force feedback device, which is the bridge between the operator and the virtual environment, and the computer is used for the construction of virtual objects and the calculation of force feedback during the interaction. The interaction process is the operator input signal, the computer will be based on the interaction mode in the virtual environment to calculate the feedback force, and with the force feedback device to the operator, so that the operator receives the haptic signal and issues the corresponding judgment and instructions to achieve the real tactile sensation of interaction with the virtual environment, and experience the force of contact with virtual objects.

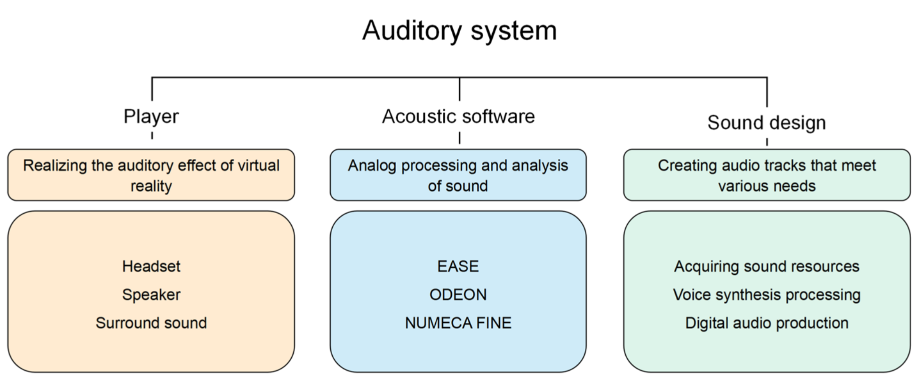

Fig. 5 Framework of auditory system composition

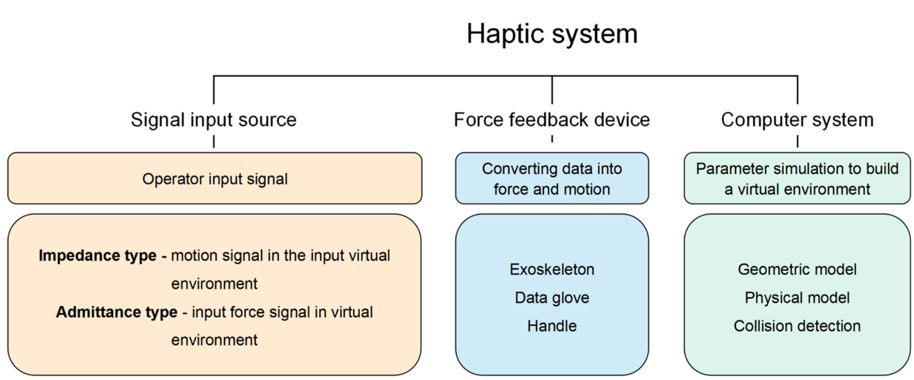

Fig. 6 Framework of haptic system composition

Exoskeletons as haptic devices have been researched: Lyu et al. [56] developed a myoelectric-controlled knee exoskeleton to assist in-home rehabilitation, controlling the flight of a bird in the virtual environment by the lifting angle of the knee joint, and the haptic feedback generated by the vibration motor in the thigh area played a punitive role when the bird hit a pipe. In addition to vibration feedback, the exoskeleton device was used in the literature [57] to provide joint impedance from zero to high to provide partial power assistance so that the patient can train within the optimal training range. Experiments have also shown that haptic feedback can provide task-oriented force feedback based on the training model, which helps to accelerate the learning process. Moreover, AxonVR [58] developed a prototype with a full-body suit that distributes an array of actuators on a flat surface that apply different pressures to the wearer's skin and change the temperature to simulate a variety of different haptic effects. There are also Senso gloves [59], which read and display information in VR while adding haptic feedback in the form of vibrations to each fingertip of the glove, bringing the simulation closer to reality. Haptic interaction can connect virtual and real-world interactions, creating a feeling of touching real objects. Currently, exoskeletons are more likely to provide feedback with strength, and delicate feedback on properties such as object shape, texture, material, temperature, and humidity still require further research.

Olfactory interaction Olfaction is a distant sensation of chemical stimulation through long-distance perception and is the most evocative of human memory [60]. In VR olfactory stimulation, artificial olfaction is achieved by simultaneously combining and vaporizing several natural chemical liquids at the same time. The principle is similar to that of digital perfume cartridges or electronic cigarettes, but its development is somewhat limited because it is difficult to collect and combine olfactory sensations and requires a large amount of data to determine the components required for different aromas. Feelreal [61] is an accessory for adding olfactory elements to VR experiences and is compatible with Oculus Rift, HTC VIVE, PlayStation VR, and other devices. It can release scents that simulate temperature humidity and wind sensation through micro heaters, water sprayers, and scent generator fans, enabling a realistic sense of wind, water mist, and scent. Feelreal comes with a series of 9 aroma cartridges that can be combined to produce up to 255 different types of scents, including flowers, food, sea oats, and gunpowder. The olfactory interaction is naturally integrated into the VR study. Figure 7 shows the olfactory simulation implementation pathway. Wang et al. [62] designed an olfactory-based AR for diagnosing machine faults and analyzed odor information by analyzing the aroma using an electronic nose. The electronic nose worked by identifying the compounds of the sample, transferring the data into a numerical pattern for the system to analyze and compare with a database with predefined aroma intensity, aroma classification, and safety index to detect the cause of machine malfunction. Olfactory interaction has a special connection with virtual experience. We can use the methods of synesthesia to transform other senses into an olfactory experience, and we can also use olfaction to enhance the functions of other senses. When users wear an exoskeleton to walk in virtual scenes, they can use olfaction for spatial positioning and guidance, and when users wear exoskeletons to complete tasks, olfaction can provide information and enhance the experience. Therefore, there is much to explore in the olfactory experience in simulation environments combined with an exoskeleton in the future.

Gustatory interaction Gustation is the stimulation of taste organs by chemical molecules of food and produces a proximate sense. Taste and smell are often associated, with sweet, sour, bitter, and salty being the gustatory sensations we often perceive. Because taste is distinguished by the nerves on the tongue, the process of gustatory perception is also a contact between the tongue and the food surface; thus, gustatory receptors are also involved in tactile perception. Although the study of gustatory sensation started early, the exploration of virtual gustatory sensation is still in its infancy. Figure 8 illustrates the pathway of gustatory simulation implementation. Kerruish [63] summarized that many devices use electrical stimulation of the sense of taste, which produces fuzzy, acidic, or metallic sensations. Furthermore, taste can be stimulated by heating around the mouth, which can

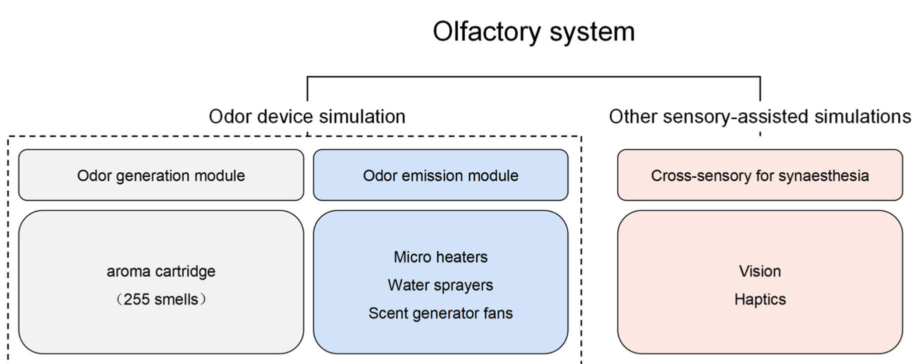

Fig. 7 Framework of olfactory system composition

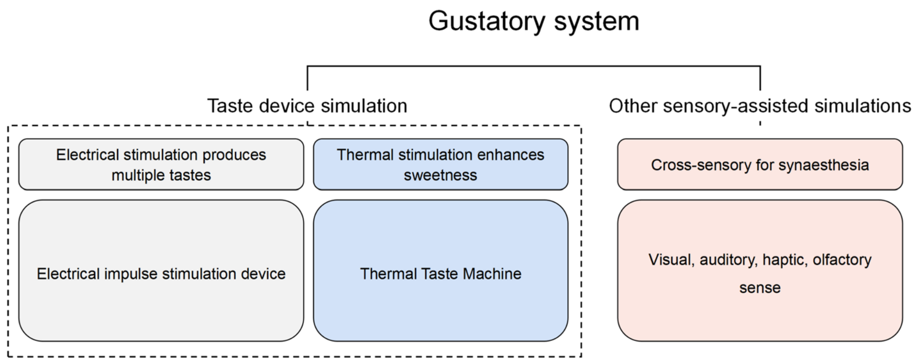

Fig. 8 Framework of gustatory system composition

produce a sweet gustatory experience, and user interfaces have been designed to simulate the sensation of drinking using recorded sounds, pressure, and vibrations. Karunanayaka et al. [64] developed a non-chemical digital taste actuation technology to design a thermal taste machine that enhances and modifies sweet gustatory sensations. By placing a silver plate on the tongue, the user can feel thermal tastes, including sweetness, mint sensation, fat sensation, and inductance. The device can change the temperature of the tongue surface in a short time, and experiments have shown that a faster temperature rise may produce a more intense sweet sensation. Gustatory actuation technology can enable the integration of gustatory experience into VR, bridging the five basic senses and facilitating a haptic simulation, which can more naturally assist users to act with exoskeletons in VR. Innovations in gustatory interaction will create a quantum leap in the field of VR.

4.2 Interaction and experience of multiple senses

Multisensory integration not only provides a richer experience but also generates the phenomenon of synesthesia, where the experience of one sense can stimulate the triggering of another sense, creating an interaction [65]. Tepljakov et al. [66] described a prototype of acoustic sound positioning, processing, and visualization to induce an interoceptive experience in a VR environment. Multisensory interoperability and interfusion create stimuli from physiological and psychological aspects, resulting in the interaction and experience of the user with the virtual world. In a broad sense, the so-called interaction means that the product can be touched, seen, heard, and felt: a process in which there exists a basic interaction of user perception and product feedback. Such interactions remain at the most basic level of feeling, and in the advanced interaction stage, users will take the initiative to understand the functions, get the desired product information, actively learn how to use the system, and be able to create new thinking and ideas during the process [67]. As users experience a new product, previous interactions and expectations are transformed into knowledge, thus constituting an experience cycle [68]. Interaction design has a participatory nature, and designers treat the product use process as a user scenario, leading users to fully engage in the product use process, thus realizing the three levels of sensory, behavioral, and emotional interaction. Experience design focuses on the whole picture, creating value for users from multiple dimensions such as user portraits, behavior, scenarios, and environments, expanding the scope of attention from the user process to the whole life cycle of the product. This will guide product iteration and updates while optimizing and innovating the user body in more dimensions.

Through the study of the five senses in VR application and architecture, we can conclude that the current virtual experience in the visual, auditory, and haptic aspects of the research is superior, the technology is more mature, and the system composition is clearer; the research on the other two senses is less developed. As intelligent devices that coordinate and cooperate with people [69], the integration and development of exoskeleton technology will show the interaction form led by seeing, hearing, and touching, and promote the research and development of other senses, so that the five senses can appropriately cooperate and serve the design content, collaborate, and optimize the experience. With the interplay and integration of visual, auditory, haptic, olfactory, and gustatory senses, the exoskeleton-based VR system can realize anthropomorphic, immersive, and intelligent interactions, providing users with rich experience, which will help VR be widely used in medical rehabilitation, industrial training, teaching, games, entertainment, etc. Figure 9 shows the interaction mode and architecture of multisensory information in VR.

4.3 Literature analysis

To understand the application and research of each sensory interaction in VR and to explore the research adaptability of perceptual interaction and the VR system combined with the exoskeleton, we conducted a literature collation on the Web of Science platform, which led to the following conclusions (Table 3). (1) Visual is the most important interaction

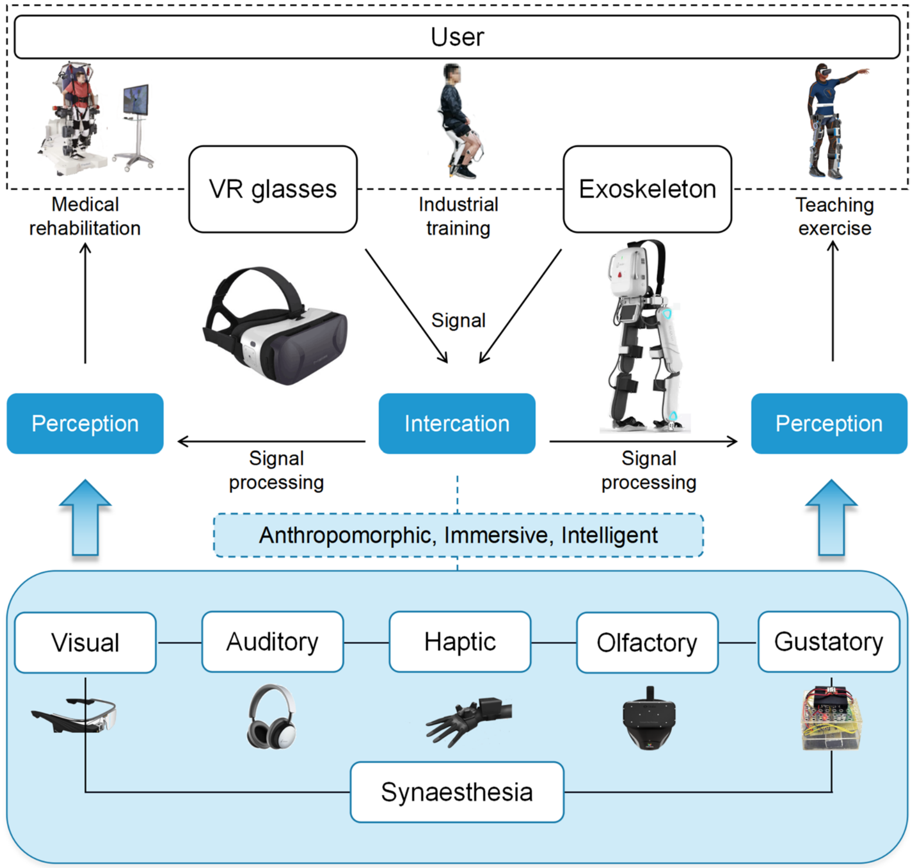

Fig. 9 Architecture and modes of a multisensory interaction

Table 3 Research and comparison of multisensory interactions from the Web of Science platform

Category	Literature	Sensory	Basic principle	Maturity	Data volume	Cited Frequency	VR applicability	Exoskeleton adaptability
Five Senses	[51, 52]	Visual	Light acts on the visual organs to communicate	High	17,061	147,275	High	Low
	[53, 54]	Auditory	Binaural eardrum's sound wave conversion vibration	General	2920	22,521	High	General
	[56, 57]	Haptic	The receptors respond to external stimuli	General	6982	64,374	High	High
	[61, 62]	Olfactory	Feel the chemical stimulation through long distances	Low	442	2447	General	Low
	[63, 64]	Gustatory	Chemical molecules stimulate the taste organs and produce closeness	Low	238	1058	General	Low
Synesthesia	[66]	Synesthesia	Stimulus of one sense triggers another sense	Low	51	827	High	General

mode of humans; more than 80% of external information is obtained by vision and visual interaction in VR. The number of studies on VR and vision is much larger than that of VR and other senses. The literature reached a peak of 2,104 articles in 2019, with research directions mainly in computer science and engineering; (2) Haptic interaction research is also more plentiful than auditory, olfactory, and gustatory research and has grown rapidly in the last five years, making it a popular area for future VR research; however, the high level of technical development may also limit the progress of research; and (3) the overall consideration shows that haptic interaction is the most suitable for the study of the exoskeleton and VR systems. Although research on synesthesia is not mature at present, its multisensory interaction will help to explore and innovate the presentation of sensory interaction, so it has high research potential and value.

5 Feedback technology

The bidirectional feedback of humans and machines is reflected in the following two aspects. On the one hand, the operator transmits the user's intention to the machine through physical information such as sound, gesture, touch, and physiological signals such as electroencephalogram, electrocardiogram, electrooculography, mechanomyogram, and galvanic skin response collected by the computer to realize the feedback from the human to the machine. On the other hand, the machine can read the information transmitted by the operator and provide feedback to the operator by corresponding image, sound, or force. Exoskeleton technology primarily involves haptic feedback, which can cause pressure, vibration, and other reflections, and drives the user to act or provide greater bearing, empowering multidimensionality for situational simulation, assisted movement, etc.

Force feedback is a sensing method that uses electrical or hydraulic signals to control the end devices of a robot. When operating in a VR system, the device will stimulate the skin to provide information about the reaction force during the action, which is the technical challenge of providing force haptics in VR systems [70], for example, the friction force of touching an object, the gravity force of lifting an object, and the force that cues the vibration sensation. In simulated touch, based on cable measurement of finger joint angles, hand exoskeletons apply force feedback to fingers in a simple lightweight structure [71]. In industrial production, a VR-based decision tool for exoskeleton integration can help identify the best areas for application and feedback, fine-tune the exoskeleton based on simulation results, and train workers to use different exoskeletons properly, effectively, and safely [72]. In medical rehabilitation, exoskeleton systems are powered by safe pneumatic muscles that assist the movement of the affected arm in 3D space, allowing the user to perform daily training in a virtual environment [73]. The exoskeleton is a highly representative device of force feedback technology, which can provide force haptic information acquisition as well as feedback for VR systems, opens up a bidirectional haptic sensory channel, and provides force feedback support for VR systems with rich morphology, function, and synergy modes for various needs.

Structurally, the force feedback system primarily consists of the operator, force feedback device, host computer, and display system. In the force feedback system, the host computer completes the computation of the execution program, processes the external device input, and realizes simultaneous real-time rendering of graphics, audio, and force and the output of force perception. The force feedback device allows the user to manipulate objects and feel haptic information. The display system is used to present the rendered virtual scene and help the user perceive the virtual environment through multidimensional information. Figure 10 shows the basic structure of force feedback. The steps for the implementation of the force feedback system are as follows: first, create a geometric model of the object in the virtual environment, establish the mapping relationship between the soft coefficient of the object and the force acting in the scene based on its physical characteristics, set the interaction mechanism between the force feedback device and the virtual object based on the relationship between the motion space of the force feedback device and the graphics space in the computer, and initialize the interaction device. Second, the application calculates visual, auditory, and even olfactory and gustatory sensory information in the scene. Moreover, the application processes tactile information such as the size of the feedback force and material of the object in the scene. Finally, based on the calculated graphic and audio information, the corresponding scene is drawn, and the force information is output to the force feedback device so that the user feels the haptic and other feedback from the devices.

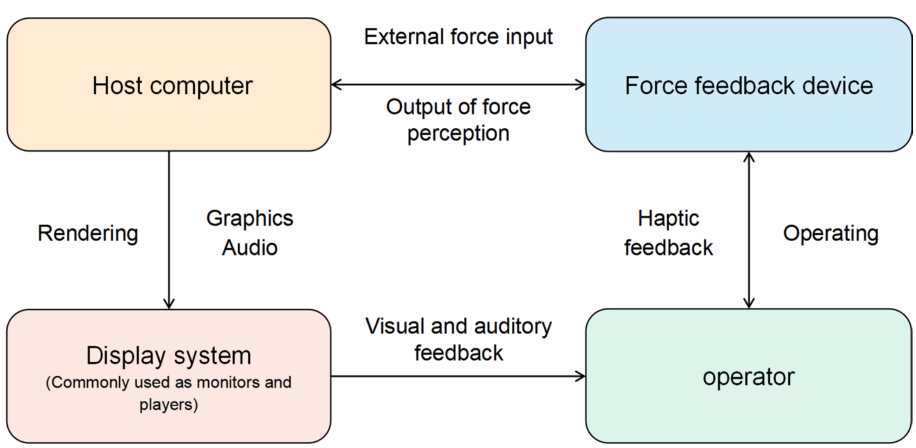

Fig. 10 Basic structure of force feedback

5.1 Operator

The operator as the subject of signal input is also the object of receiving information. Through the force feedback device, the operator inputs force, motion, gestures, and other signals. Through processing calculations and feedback transmission, the operator's sensory nerve is stimulated, and information is conducted to the human nerve center and the brain according to the received tactile signal to issue the corresponding judgment and instructions [74]. The system using the signal flow mode can also be divided into impedance and admittance types [75]. The impedance type flow method, such as Phantom [76], means that the input signal transmitted to the virtual environment by the operator through the force feedback device is a motion signal, and the signal output to the force feedback device and transmitted back to the operator is a force signal. Admittance-type flow methods such as Haptic-Master [77] refer to the signal transmitted to the virtual environment for the force signal, and the signal of the motion amount is calculated using the virtual object model. Force feedback technology allows the operator to perceive and manipulate objects in the virtual environment in conjunction with the real environment, which greatly improves the realism and immersion of the VR system.

5.2 Force feedback device

The force feedback device is the interface of the haptic interaction system, which can transform the data transmitted in the virtual environment into corresponding force and motion, and then provide feedback to the operator. Force feedback devices have bidirectional channels, whereas other visual or auditory devices have only unidirectional information flow in the sensory channel [78]. Force feedback devices can also change or manipulate the virtual environment through human intervention, and the equipment needs to have the following properties: First, to make people feel a real sense of touch, the mechanical structure and sensor accuracy requirements are extremely high. Second, to make the wearing as comfortable as possible, the choice of flexible structures and materials is also very important. Figure 11 presents the basic structure of the force feedback device: the signal is processed through the controller and by the computer to the drive board; it is amplified by the actuator to produce haptics; and finally feedback is provided by the mechanical transmission device to the operator.

There are many well-developed force feedback devices used in VR systems, such as the Phantom Omni from Geomagic, a three-degree-of-freedom force feedback device that has become increasingly popular [79]. DELTA by the Swiss company Force Dimension has low inertia, high stiffness, and high work rate repeatability [80]. The FALCON set-up device from NOVINT can be seen as a relatively low-cost three degrees of freedom haptic device, and the design is based on a three-degree-of-freedom DELTA parallel robot, which is primarily used in the gaming field [81]. Virtouse series from Haption is a self-managed tactile device with a wide range of activities and can withstand large forces and torques, which is mainly used in industrial assembly, aerospace maintenance, bioengineering, and other fields [82]. The Cyber Grasp from Immersion in the USA is a multifunctional VR device consisting of many sensors on the glove, which perceives movement, grasping, and rotation in virtual space by the glove through software mapping [83]. IBM's TrackPoint device is a strain gauge based on two-axis force sensors that can remap the output to force data based on the transfer function and can be optimized based on two degrees of freedom [84]. Currently, hand-based force feedback devices are more developed and widely used, and haptic interactions by other parts require the exploration and application of exoskeleton technology for a more comprehensive and realistic implementation of haptic feedback. According to the above literature research, the research on exoskeletons as feedback devices in VR is increasing every year. In the feedback of the upper-limb exoskeleton, Fangquan Liu [85] developed a remote upper-limb exoskeleton rehabilitation system with five degrees of freedom, which can provide user training for internal/external rotation of the shoulder joint, anterior/posterior traction, internal/external rotation of the upper arm, elbow extension/flexion, and internal/external rotation of the forearm, and showed the training effect and training scenes through the human–machine interface of VR. In the feedback of the lower limb exoskeleton, C.T Pan [86] designed a lower limb exoskeleton according to the proportions of human lower limbs and combined it with VR images to make the rehabilitation more interesting. The exoskeleton has a stable structure, and four servo motors are installed on the left and right sides of the hip and knee, and a PID

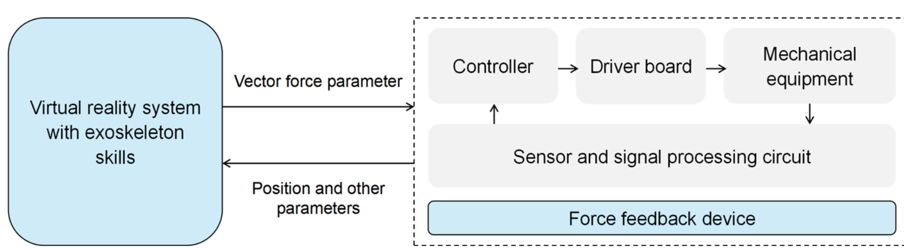

Fig. 11 Structure diagram of force feedback device

controller was used to assist and process the motor feedback. While whole-body exoskeletons as feedback devices have been less studied, most of them are partially structured to accomplish some type of feedback function. Gerald P. Roston [87] produced a whole-body motion perception display device for VR applications that allows the operator to interact with real walls, windows, doors, and other vertical obstacle features in the motion space. The design of this complex device was driven by various requirements, including the need for system modularity and enhanced security and the need to simulate all significant physical activities.

5.3 Host computer

The computer is an important part of the system used for the construction of the virtual environment and objects and is responsible for the computation of force feedback during interaction.

Regarding model construction, parametric modeling is a method of turning a designed object into a set of principles encoded as a sequence of parametric equations that are used to represent certain quantities as explicit functions of some variables, and by changing any parameter in the equation, a new shape can be generated [88]. Parametric modeling is used to establish and analyze the geometric, material, temperature, and other property parameters of the object. Parametric modeling is divided into geometric and physical modeling. The scope of the design parameters is the geometric model, but the geometric model cannot be used directly to perform analytical calculations, so it needs to be transformed into a finite element model, which is the parameterization of the physical model. Geometric modeling involves shaping the appearance characteristics of objects, such as shape, color, texture, and material, by manual or automatic modeling. Commonly used modeling software includes OpenGL [89], Blender [90], and AutoCAD [91], which can also use 3D scanners to model actual objects to present visual effects. Physical modeling has added some constraints based on geometric modeling so that the virtual model is more in line with the corresponding real-world mass, deformation, damping, surface roughness, inertia, and other physical properties of the object. The common modeling methods include finite element method [92], discrete element method [93], and boundary element method [94]. These use differential equations to form a dynamical system, so that the virtual objects built in the visual and tactile domain can achieve realistic effects.

For the feedback calculation, collision detection is performed after modeling the virtual environment and the objects and simulating the forces on the objects. Collision detection is a critical aspect of haptic feedback in VR, and the collision point location and other information need to be accurately calculated to ensure the fidelity of the system and user immersion [95]. The spatial decomposition method (SDM) and hierarchical bounding box (HBB) are widely used. The SDM is used to analyze and visualize the directional characteristics of the impulse response by equating the completely virtual environment into small cells of the same volume and then simplifying the collision detection process into an intersection test of adjacent cells or the same cell. This has also been successfully applied to the study of acoustic space [96]. The HBB is used to surround and replace the object to be modeled by a geometry with a simple structure and a slightly larger volume than the virtual object, so the interaction between virtual objects can be known by detecting the collision between the bounding boxes. If the intersection region is detected, fine collision detection between objects is performed, and if the enclosed objects do not intersect, collision detection between objects ends [97]. The bounding box methods can reduce the number of collision detections and test time consumption [98] with representative algorithms.

5.4 Display system

The display system delivers information other than haptic information to the user, such as rendered images, sounds, and even flavors, and works with force feedback devices to present information of many dimensions. Studies have shown that a slight delay in force feedback can cause instability for the user, so other information can be used to transform or replace force feedback information [99]. Visual and auditory information flow is a unidirectional perceptual channel, and they allocate relatively large areas in the sensory cortex that do not cause instability in the presence of time delays, suggesting that visual and auditory information can enhance the realism of force feedback information. Currently, mainstream open-source force feedback interfaces, such as OpenHaptics [100] and CHAI3D [101], support the development of applications that integrate vision and force perception. OpenHaptics from SenseAble is a development toolkit for Phantom series force feedback devices, which can complete the integration of geometric models and physical properties and the interactive simulation of force feedback devices. It includes three different levels of interface libraries: QuickHaptics API, Haptic Device API, and Haptic Library API. The Haptic Library API is built based on the Haptic Device API and provides a high level of haptic rendering [102]. Stanford University's CHAI3D is a development toolkit that supports a variety of force feedback devices, and it has good scalability and supports the design of new algorithms based on existing visual and haptic rendering algorithms [103]. Regarding the development of auditory-haptic interfaces, Nikolaos Kaklanis [104] developed a tool for generating haptic and auditory feedback using open street map data, and a speech mechanism provides audio navigation during the haptic exploration of the map. Jules Françoise [105] designed SoundGuides, providing users with continuous sound feedback for motion interaction, allowing sound synthesis and feedback through gestures designed by users.

5.5 Literature research

For a VR system applying exoskeleton technology, force feedback technology is the most complex and important technology for achieving bidirectional feedback. After understanding the definition, application, and working principle of force feedback technology, we defined the four components: the operator, force feedback device, host computer, and display system. Then, we conducted a separate subject search on the Web of Science platform, obtaining the following conclusions. (1) Force feedback devices are the core of the technology, have the largest number of studies, are developed with a high degree of difficulty, are currently focused on hand feedback, and do not constitute mature industrialization and commercialization. (2) There is very little research on the theme of the display system, indicating that the synchronous rendering of other sensory and haptic devices still has much room for exploration. (3) Comprehensive analysis shows that the exoskeleton, as a typical application of human–machine fusion intelligence, can meet the haptic feedback of all parts of the body, with high research value and application prospects. Thus, users can truly follow human body language for natural human–machine interaction and information exchange and obtain the same sense of motion as when touching actual objects, which produces a more realistic sense of immersion (Table 4).

6 Discussion and conclusion

The development of VR introduces a new dimension to human life and provides a refreshing and high-quality experience. Its main technologies are environmental simulation, multidimensional interaction, and feedback devices. The exoskeleton, as an intelligent human–machine system device that mimics the musculoskeletal structure of the human body, is a device that can address the current needs of people's lives and is essential in future society. The combination of exoskeletons and VR has been a research trend in recent years. Currently, most literature discusses an overview of the research in a particular application scenario or shows the solution to a specific problem, which lacks comprehensive and extensive systematic combing. Therefore, it is worthwhile to consider and explore the direction of better integration and development of the exoskeleton and VR system by refining the three operation processes of recognition, perception, and feedback and the three points of positioning technology, multisensory interaction, and feedback technology.

- Establishing comprehensive and in-depth positioning methods

  After exploring the three categories of positioning methods, we can understand the technical forms applicable to the study of the exoskeleton and VR. To build the most suitable positioning system, it is necessary to consider both the mode and configuration. The mode mainly considers the adaptability to the user operation mode, avoiding the physiological and psychological rejection of the operator, and whether it can fit the research pur-

Table 4 Research and comparison of force feedback technology from the Web of Science platform

Technology	Literature	Content	Basic principle	Significance	Data volume	Cited frequency	VR applicability	Exoskeleton adaptability
Force feedback technology	[76, 77]	Operator	Subject of signal input and the object of receiving information	High	1931	23,340	High	High
	[80–87]	Force feedback device	Turn the transmitted data into force and feedback	Very high	4549	40,763	High	High
	[86–95]	Host computer	Building a virtual environment and calculating power feedback	High	1718	22,814	High	Low
	[100–105]	Display system	Delivering information other than tactile to users	General	97	1622	High	General

pose and product functionality to the maximum extent. The configuration is based on the requirements of the environment, such as the site, light, settings, and other factors. Based on the full integration of the exoskeleton and VR, a high-quality, low-cost, and easy-to-build and disassemble positioning technology configuration is required.

- Exploring abundant and natural interaction methods

  At present, the interaction of VR has high research quantity and deeper investigation of visual, auditory, and haptic. Therefore, the architecture of its interactive system is also comprehensive and standardized. In contrast, the research on olfaction and gustation is insufficient to constitute a system. Existing exoskeletons can achieve the protection and drive of the musculoskeletal system, and it is necessary to further study more interaction modes of human–machine collaboration. We use the VR system of the exoskeleton as the carrier to explore the interoperability and integration of the five senses and compare the relationships between the operations. The five senses are relatively independent, but they can also assist each other. For example, people usually transform and enhance their senses using synesthesia. Therefore, connecting the five senses and innovating their interaction can further enhance the anthropomorphic, immersive, and intelligent experience of the VR system and be widely used in intelligent fields.

- Innovating intelligent and mature feedback devices

  In this study, after standardizing the type of exoskeleton based on the human–machine–environment synergy mode, the integration mode of the exoskeleton and VR can be established. Many of the current VR feedback devices use hand feedback. There is still much room for research on exoskeletons as force feedback devices, especially for lower limb exoskeletons and whole-body exoskeletons. At the same time, research on the operator, host computer, and display system is still at the basic stage, and no exoskeleton-centric research has been launched. Therefore, research on exoskeletons as feedback devices in VR can contribute to the innovative development of more intelligent and mature products, which is the development direction for future intelligent life.

The VR system applied with exoskeleton technology is a fusion and innovation of two technologies across hardware and software mediums. In this paper, for the first time, the basic cognitive and synergistic patterns of the two technologies are completely separated from the main processes of human interaction. The research content is summarized as positioning technology, multisensory interaction, and feedback technology. We summarize the technical principles, model architecture, application studies, and in-depth studies of the performance characteristics of the cutting-edge methods and the connections between them. We also summarize and contextualize the suitability of each technology and research direction for VR and exoskeletons to explore the current shortcomings and possible directions for development. In this paper, we hope to provide an overview of new research on VR systems to provide a reference for the holistic comprehensive expansion of VR systems applying exoskeleton technology.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Zhou, N.-N., Deng, Y.-L.: Virtual reality: a state-of-the-art survey. Int. J. Autom. Comput. **6**, 319–325 (2009). https://doi.org/10.1007/s11633-009-0319-9
2. Ken, I., Toni, D.L., Remy, E., et al.: Spider hero: entertainment VR with pulling force. J. Inst. Image Inf. Telev. Eng. **66**, J11–J16 (2012). https://doi.org/10.3169/itej.66.J11
3. Guo, J., Guo, S.: Design and characteristics evaluation of a novel VR-based robot-assisted catheterization training system with force feedback for vascular interventional surgery. Microsyst. Technol. **23**, 3107–3116 (2017). https://doi.org/10.1007/s00542-016-3086-x
4. Luisier, Y.D.: Perceptions of Thai aviation students on consumer grade VR flight experiences. Proceedings **39**, 888 (2019)
5. He, W.-L., Song, Y.-X., Qiu, Y., et al.: On the application of BIM+VR technology in building protection. Value Eng. **39**, 8 (2020). https://doi.org/10.1007/s00542-016-3086-x
6. Zhiyong, Z., Hesong, L., Guojun, Q., et al.: Research on the defense education mode of immersive colleges and universities based on virtual reality technology. Univ. Educ. **2**, 11 (2018)
7. Miaozong, D., Junmin, D.: Research status and problems of exoskeleton robots. Modern Manuf. Eng. **3**, 855 (2019)
8. Ma, W., Huang, R., Chen, Q., et al.: Dynamic movement primitives based parametric gait model for lower limb exoskeleton. In: In 2020 39th Chinese Control Conference (CCC). IEEE, pp. 3857–3862, (2020) https://doi.org/10.23919/CCC50068.2020.9188594
9. Kapsalyamov, A., Hussain, S., Jamwal, P.K.: State-of-the-art assistive powered upper limb exoskeletons for elderly. IEEE Access **8**, 178991–179001 (2020). https://doi.org/10.1109/access.2020.3026641
10. Ishiguro, Y., Makabe, T., Nagamatsu, Y., et al.: Bilateral humanoid teleoperation system using whole-body exoskeleton cockpit TABLIS. IEEE Robot. Autom. Lett. **5**, 6419–6426 (2020). https://doi.org/10.1109/LRA.2020.3013863
11. Sun, Z., Bao, G., Li, X.: Experimental research of force feedback dataglove based on pneumatic artificial muscle. Chin. J. Mech. Eng. **2**, 489 (2009). https://doi.org/10.3901/CJME.2009.04.489
12. Wei, D.: Lower limb exoskeleton robot based on human-robot cooperation strategy. In: University of Science and Technology of China (2011)

13. Gancet, J., Ilzkovitz, M., Cheron, G., et al.: MINDWALKER: a brain controlled lower limbs exoskeleton for rehabilitation. Potential applications to space. In: 11th Symposium on advanced space technologies in robotics and automation (Vol. 1, pp. 12-14). (2011) https://www.researchgate.net/publication/265752194
14. Ferrero, L., Ortíz, M., Quiles, V., et al.: Improving motor imagery of gait on a brain-computer interface by means of virtual reality: a case of study. IEEE Access **9**, 49121–49130 (2021)
15. Sakagami, Y., Watanabe, R., Aoyama, C., et al.: The intelligent ASIMO: system overview and integration. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 3, pp. 2478–2483. IEEE. (2002) https://doi.org/10.1109/IRDS.2002.1041641
16. Lee, Y., Ryoo, Y. J., Choi, J., et al.: Intelligent machine space for interacting with human in Ubiquitous Virtual Reality. In: International Conference on Distributed, Ambient, and Pervasive Interactions, pp. 459–465. Springer, Berlin, Heidelberg. (2013) https://doi.org/10.1007/978-3-642-39351-8_50
17. Gancet, J., Ilzkovitz, M., Motard, E., et al.: MINDWALKER: Going one step further with assistive lower limbs exoskeleton for SCI condition subjects. In: 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 1794–1800. IEEE. (2012) https://doi.org/10.1109/BioRob.2012.6290688
18. Soleimani Amiri, M., Ramli, R., Ibrahim, M.F., et al.: Adaptive particle swarm optimization of PID gain tuning for lower-limb human exoskeleton in virtual environment. Mathematics **8**(11), 2040 (2020). https://doi.org/10.3390/math8112040
19. Analytics, C.: Web of Science. Trust the Difference, Web of Science Fact Book (2017)
20. Scott, J.: Social network analysis. Sociology **22**, 109–127 (2016). https://doi.org/10.1177/0038038588022001007
21. Bastian, M., Heymann, S., Jacomy, M.: Gephi: an open source software for exploring and manipulating networks. In: Proceedings of the International AAAI Conference on Web and Social Media (2009)
22. Wei, S.: Research of virtual reality training system for robot-assisted upper limb rehabilitation. In: Shanghai Jiao Tong University (2012)
23. Zhang, Y.: Development of an exoskeleton system for children's exercise capacity promotion and its experimental study. In: Zhejiang University (2013)
24. Karvouniari, A., Michalos, G., Dimitropoulos, N., et al.: An approach for exoskeleton integration in manufacturing lines using Virtual Reality techniques. Procedia CIRP **78**, 103–108 (2018). https://doi.org/10.1016/j.procir.2018.08.315
25. Secco, E.L., Tadesse, A.M.: A wearable exoskeleton for hand kinesthetic feedback in virtual reality. In: International Conference on Wireless Mobile Communication and Healthcare. Springer, pp. 186–200 (2019)
26. Mubin, O., Jishtu, N., Alsinglawi, B., et al.: Exoskeletons with virtual reality, augmented reality or gamification for stroke patients' rehabilitation. JMIR Rehabil. Assistive Technol. **6**, 555 (2018)
27. Jiang, Y., Qiao, B., Zhao, Y.: Review of reduced gravity simulation for astronaut training. Manned Spaceflight **2**, 744 (2018)
28. Zhang, Y.-X., Ren, S.: Overview of application of positioning technology in virtual reality. Comput. Sci. 48: 308–318. https://doi.org/10.11896/jsjkx.200800010
29. Brena, R.F., García-Vázquez, J.P., Galván-Tejada, C.E., et al.: Evolution of indoor positioning technologies: a survey. J. Sens. **2017**, 211 (2017). https://doi.org/10.1155/2017/2630413
30. Wang, Y., Lin, J.: Indoor location technique based on RFID. China Instrum. **2**, 54–57 (2011)
31. NaturalPoint, Motion Capture Systems-OptiTrack Webpage., https://optitrack.com/
32. Kilteni, K., Bergstrom, I., Slater, M.: Drumming in immersive virtual reality: the body shapes the way we play. IEEE Trans. Visual Comput. Gr. **19**, 597–605 (2013). https://doi.org/10.1109/TVCG.2013.29
33. Büyüksalih, G., Kan, T., Özkan, G.E., et al.: Preserving the knowledge of the past through virtual visits: from 3D laser scanning to virtual reality visualisation at the Istanbul Çatalca İnceğiz Caves. PFG-J. Photogramm. Remote Sens. Geoinform. Sci. 88:133-146, (2020) https://doi.org/10.1007/s41064-020-00091-3
34. Vive.com. (2018). VIVE™ Discover Virtual Reality Beyond Imagination, https://www.vive.com/eu/
35. Spitzley, K.A., Karduna, A.R.: Feasibility of using a fully immersive virtual reality system for kinematic data collection. J. Biomech. **87**, 172–176 (2019). https://doi.org/10.1016/j.jbiomech.2019.02.015
36. Lou P, Zhang, H., Zhang, X., et al.: Fundamental analysis for indoor visible light positioning system. In: 2012 1st IEEE International Conference on Communications in China Workshops (ICCC). IEEE, pp. 59–63, (2012) https://doi.org/10.1109/ICCCW.2012.6316475
37. Huang, C., Zhang, X.: Impact and feasibility of darklight LED on indoor visible light positioning system. In: 2017 IEEE 17th International Conference on Ubiquitous Wireless Broadband (ICUWB). IEEE, pp. 1–5, (2017) https://doi.org/10.1109/ICUWB.2017.8250973
38. PlayStation 4 Specifications, http://us.playstation.com/ps4/features/techspecs/index. htm
39. Lange, B., Rizzo, A., Chang, C.-Y., et al.: Markerless full body tracking: depth-sensing technology within virtual environments. In: Interservice/industry Training, Simulation, and Education Conference (I/ITSEC). Citeseer (2011)
40. Gao, Q.H., Wan, T.R., Tang, W., et al.: A stable and accurate marker-less augmented reality registration method. In: 2017 International Conference on Cyberworlds (CW). IEEE, pp. 41–47, (2017) https://doi.org/10.1109/CW.2017.44
41. Dijaya, R., Kom, S., Kom, M., et al.: Virtual reality markerless based on 3D for the representation of heart and circulatory system. J. Adv. Res. Dyn. Control Syst. **2**, 888 (2021)
42. Hirschmanner, M., Tsiourti, C., Patten, T., et al.: Virtual reality teleoperation of a humanoid robot using markerless human upper body pose imitation. In: 2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids). IEEE, pp. 259–265, (2019) https://doi.org/10.1109/Humanoids43949.2019.9035064
43. Bicho, D., Girão, P., Paulo, J., et al.: Markerless multi-view-based multi-user head tracking system for virtual reality applications. In: 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC). IEEE, pp. 2645–2652, (2019) https://doi.org/10.1109/SMC.2019.8914350
44. Chen, Y.: Active vision positioning technology for immersive virtual reality. In: Chongqing University of Posts and Telecommunications (2017)
45. Lee, J., Sinclair, M., Gonzalez-Franco, M., et al.: TORC: A virtual reality controller for in-hand high-dexterity finger interaction. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1–13, (2019) https://doi.org/10.1145/3290605.3300301
46. Albert, R., Patney, A., Luebke, D., et al.: Latency requirements for foveated rendering in virtual reality. ACM Trans. Appl. Percept. **14**, 1–13 (2017). https://doi.org/10.1145/3127589
47. Yue, M., Ning, Y., Yu, S., et al.: Composite following control for wheeled inverted pendulum vehicles based on human-robot interaction. Sci. China Inf. Sci. **62**, 1–3 (2019). https://doi.org/10.1007/s11432-018-9696-2

48. Ping, Y.: The application of list method in the teaching of "Psychology''-a brief table of "Psychology''. J. Fuqing Branch Fujian Normal Univ. **2**, 555 (1990)
49. Jie, X.: Study on propagation of visual culture and the routinization of ideology. Soc. Stud. **5**, 68–74 (2016)
50. Guan, H.: The research and implementation of the silk road virtual reality system catering to multi-sensory experience. In: Zhejiang University (2015)
51. Zhao, H., Swanson, A.R., Weitlauf, A.S., et al.: Hand-in-hand: a communication-enhancement collaborative virtual reality system for promoting social interaction in children with autism spectrum disorders. IEEE Trans. Hum.-Mach. Syst. **48**, 136–148 (2018)
52. Shi, P., Zheng, J., Yu, H.: A virtual reality training system based on upper limb exoskeleton rehabilitation robot. In: Proceedings of the 12th International Convention on Rehabilitation Engineering and Assistive Technology, pp. 138–141 (2018)
53. Jiang, L., Masullo, M., Maffei, L., et al.: A demonstrator tool of web-based virtual reality for participatory evaluation of urban sound environment. Landsc. Urban Plan. **170**, 276–282 (2018). https://doi.org/10.1016/j.landurbplan.2017.09.007
54. Wu, Q., Wang, X., Chen, B., et al.: Patient-active control of a powered exoskeleton targeting upper limb rehabilitation training. Front. Neurol. **9**, 817 (2018). https://doi.org/10.3389/fneur.2018.00817
55. Zhou, J.-L.: The local characteristics tableware design based on the consumer tactile experience and memory. Packag. Eng. **38**, 71–74 (2017)
56. Lyu, M., Chen, W.-H., Ding, X., et al.: Development of an EMG-controlled knee exoskeleton to assist home rehabilitation in a game context. Front. Neurorobot. **13**, 67 (2019). https://doi.org/10.3389/fnbot.2019.00067
57. Zhang, S., Fu, Q., Guo, S., et al.: Coordinative motion-based bilateral rehabilitation training system with exoskeleton and haptic devices for biomedical application. Micromachines **10**, 8 (2019). https://doi.org/10.3390/mi10010008
58. Bailey, D.E.: The potential for immersive technology combined with online dating. J. Telecommun. Dig. Econ. **5**, 125 (2017)
59. Nainggolan, F., Siregar, B., Fahmi, F.: Design of interactive virtual reality for erection steel construction simulator system using senso gloves. In: Journal of Physics: Conference Series. IOP Publishing, pp. 012019, (2020) https://doi.org/10.1088/1742-6596/1542/1/012019
60. Porteous, J.D.: Smellscape. Prog. Phys. Geogr. **9**, 356–378 (1985). https://doi.org/10.1177/030913338500900303
61. Pirkkalainen, H., Torro, O.: Emerging Technology Adoption and Use: Consolidated Assignments from Spring 2020, (2020) http://urn.fi/URN:ISBN:978-952-03-1572-6
62. Wang, J., Erkoyuncu, J., Roy, R.: A conceptual design for smell based augmented reality: case study in maintenance diagnosis. Procedia CIRP **78**, 109–114 (2018). https://doi.org/10.1016/j.procir.2018.09.067
63. Kerruish, E.: Arranging sensations: smell and taste in augmented and virtual reality. Sens. Soc. **14**, 31–45 (2019). https://doi.org/10.1080/17458927.2018.1556952
64. Karunanayaka, K., Johari, N., Hariri, S., et al.: New thermal taste actuation technology for future multisensory virtual reality and internet. IEEE Trans. Visual Comput. Gr. **24**, 1496–1505 (2018). https://doi.org/10.1109/TVCG.2018.2794073
65. Ross, M.: Virtual reality's new synesthetic possibilities. Telev. New Media **21**, 297–314 (2020). https://doi.org/10.1177/1527476418805240
66. Tepljakov, A., Astapov, S., Petlenkov, E., et al.: Sound localization and processing for inducing synesthetic experiences in virtual reality. In: 2016 15th Biennial Baltic Electronics Conference (BEC). IEEE, pp. 159–162, (2016) https://doi.org/10.1109/BEC.2016.7743753
67. Liu, Y.: Social interaction design of appliance brand under new retail background. In: Jiangnan University (2019)
68. Qian, G.: Research on the periodicity of user experience in the time dimension. Theor. Res. **2**, 12 (2017)
69. Zhao, Y., Xu, C., Zhang, et al.: Key technological analysis and study on exoskeleton of human-body lower limbs. J. Mach. Des. **25**, 1–5 (2008)
70. Mcneely, W.A.: Robotic graphics: a new approach to force feedback for virtual reality. In: Proceedings of IEEE Virtual Reality Annual International Symposium. IEEE, pp. 336–341, (1993) https://doi.org/10.1109/VRAIS.1993.380761
71. Park, Y., Jo, I., Lee, J., et al.: A dual-cable hand exoskeleton system for virtual reality. Mechatronics **49**, 177–186 (2018). https://doi.org/10.1016/j.mechatronics.2017.12.008
72. Salvatore, M., Stefano, R.: Smart operators: How Industry 4.0 is affecting the worker's performance in manufacturing contexts. Procedia Comput. Sci. **180**, 958–967 (2021). https://doi.org/10.1016/j.procs.2021.01.347
73. Huang, J., Tu, X., He, J.: Design and evaluation of the RUPERT wearable upper extremity exoskeleton robot for clinical and in-home therapies. IEEE Trans. Syst. Man Cybern. Syst. **46**, 926–935 (2015). https://doi.org/10.1109/TSMC.2015.2497205
74. Li, J., Qi, Y., Wang, X., et al.: A review of the research and applications of force feedback devices based on virtual reality. Mech. Sci. Technol. Aerosp. Eng. **30**, 1107–1111 (2011)
75. Lei, X.: Research on system stability for haptic interaction. In: Nanchang University (2015)
76. Massie, T.H., Salisbury, J.K.: The phantom haptic interface: a device for probing virtual objects. In: Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. Chicago, IL, pp. 295–300 (1994)
77. Van Der Linde, R.Q., Lammertse, P., Frederiksen, E., et al.: The HapticMaster, a new high-performance haptic interface. In: Proceedings of Eurohaptics. Edinburgh University, pp. 1–5, (2002)
78. Maeda, R.S., Gribble, P.L., Pruszynski, J.A.: Learning new feedforward motor commands based on feedback responses. Curr. Biol. **30**(1941–1948), e1943 (2020). https://doi.org/10.1016/j.cub.2020.03.005
79. Verner, L.N., Okamura, A.M.: Force & torque feedback vs force only feedback. In: World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. IEEE, pp. 406–410, (2009) https://doi.org/10.1109/WHC.2009.4810880
80. Qin, H., Song, A., Liu, Y., et al.: Design and calibration of a new 6 DOF haptic device. Sensors **15**, 31293–31313 (2015). https://doi.org/10.3390/s151229857
81. Karbasizadeh, N., Zarei, M., Aflakian, A., et al.: Experimental dynamic identification and model feed-forward control of Novint Falcon haptic device. Mechatronics **51**, 19–30 (2018). https://doi.org/10.1016/j.mechatronics.2018.02.013
82. Liu, L.-M., Li, W., Dai, J.-J.: Haptic technology and its application in education and learning. In: 2017 10th International Conference on Ubi-media Computing and Workshops (Ubi-Media). IEEE, pp. 1–6, (2017) https://doi.org/10.1109/UMEDIA.2017.8074138
83. Xu, Y., Dai, Y.: Review of hand gesture recognition study and application. Contemp. Eng. Sci. **10**, 375–384 (2017)
84. Han, Y., Wu, J., Xiong, Z.: A framework of multi-channel touch sensing with multiple trackpoints. In: 2017 IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM). IEEE, pp. 644–649, (2017) https://doi.org/10.1109/ICCIS.2017.8274853
85. Liu, F., Han, X., Lin, M., et al.: Remote Upper Limb Exoskeleton Rehabilitation Training System Based on Virtual Reality. In:

2019 16th International Conference on Ubiquitous Robots (UR). IEEE, pp. 323–327, (2019) https://doi.org/10.1109/URAI.2019.8768618
86. Pan, C., Lin, Z., Sun, P., et al.: Design of virtual reality systems integrated with the lower-limb exoskeleton for rehabilitation purpose. In: 2018 IEEE International Conference on Applied System Invention (ICASI). IEEE, pp. 498–501, (2018) https://doi.org/10.1109/ICASI.2018.8394296
87. Roston, G.P., Peurach, T.: A whole body kinesthetic display device for virtual reality applications. In: Proceedings of International Conference on Robotics and Automation. IEEE, pp. 3006–3011, (1997) https://doi.org/10.1109/ROBOT.1997.606744
88. El Iraqi, A., El Daly, H.: Parametric modeling developement through out analogue and digital ages. J. Al-Azhar Univ. Eng. Sect. **12**, 597–611 (2017). https://doi.org/10.21608/auej.2017.19242
89. Zhao, K., Tang, L., Zhang, S.: Research on interactively 3D tree modeling and visualization based on OpenGL. J. Zhejiang A &F Univ. **36**, 138–147 (2019). https://doi.org/10.11833/isn.2095-0756.2019.01.017
90. Markova, K.T., Dovramadjiev, T.A., Jecheva, G.V.: Computer parametric designing in Blender software for creating 3D paper models. Annu. J. Tech. Univ. Varna Bulgaria **1**, 77–84 (2017). https://doi.org/10.29114/ajtuv.vol1.iss1.44
91. Lyashkov, A., Murashev, G.: Modeling of shaping process and analysis of gear wheel cutting process by means of AUTOCAD and ANSYS software. In: Journal of Physics: Conference Series. IOP Publishing, pp. 012068, (2020) https://doi.org/10.1088/1742-6596/1441/1/012068
92. Xu, W., Zeng, H., Yang, P., et al.: Numerical analysis on tractive performance of off-road tire on gravel road using a calibrated finite element method-discrete element method model and experimental validation. Proc. Inst. Mech. Eng. Part D J. Autom. Eng. **234**, 3440–3457 (2020). https://doi.org/10.1177/0954407020930175
93. Jiang, C., Zhao, G.-F., Khalili, N.: On crack propagation in brittle material using the distinct lattice spring model. Int. J. Solids Struct. **118**, 41–57 (2017). https://doi.org/10.1016/j.ijsolstr.2017.04.024
94. Gu, Y., He, X., Chen, W., et al.: Analysis of three-dimensional anisotropic heat conduction problems on thin domains using an advanced boundary element method. Comput. Math. Appl. **75**, 33–44 (2018). https://doi.org/10.1016/j.camwa.2017.08.030
95. Kao, Y.-C., Lee, C.-S., Liu, Z.-R., et al.: Case study of virtual reality in CNC machine tool exhibition. In: MATEC Web of Conferences. EDP Sciences, pp. 00004, (2017) https://doi.org/10.1051/matecconf/201712300004
96. Ahrens, J.: Perceptual evaluation of binaural auralization of data obtained from the spatial decomposition method. In: 2019 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics (WASPAA). IEEE, pp. 65–69, (2019) https://doi.org/10.1109/WASPAA.2019.8937247
97. He, Y., Song, K., Meng, Q., et al.: An end-to-end steel surface defect detection approach via fusing multiple hierarchical features. IEEE Trans. Instrum. Measur. **69**, 1493–1504 (2019). https://doi.org/10.1109/TIM.2019.2915404
98. Zhao, W., Qu, H.: Application of improved algorithm based on sphere OBB hybrid hierarchical bounding box in Teaching. In: Journal of Physics: Conference Series. IOP Publishing, pp. 012080, (2021) https://doi.org/10.1088/1742-6596/1732/1/012080
99. Richard, P., Birebent, G., Coiffet, P., et al.: Effect of frame rate and force feedback on virtual object manipulation. Presence Teleoper. Virtual Environ. **5**, 95–108 (1996). https://doi.org/10.1162/pres.1996.5.1.95
100. OpenHaptics Toolkit, The SenSable Technologies Inc., USA, http://www.sensable.com/products-openhapticstoolkit.htm/
101. CHAI3D, https://www.chai3d.org/
102. Yang, Y., Yang, P., Zeng, F., et al.: Research on interactive operation considered physical attributes by using force feedback device. In: 2017 International Conference on Security, Pattern Analysis, and Cybernetics (SPAC). IEEE, pp. 737–742, (2017) https://doi.org/10.1109/SPAC.2017.8304371
103. Kim, T., Kim, C., Song, H., et al.: Intuition accuracy and immersiveness analysis of 3D visualization methods for haptic virtual reality. Int. J. Adv. Comput. Sci. Appl. **10**, 30–37 (2019)
104. Kaklanis, N., Votis, K., Tzovaras, D.: Open touch/sound maps: a system to convey street data through haptic and auditory feedback. Comput. Geosci. **57**, 59–67 (2013). https://doi.org/10.1016/j.cageo.2013.03.005
105. Françoise, J., Chapuis, O., Hanneton, S., et al.: Soundguides: adapting continuous auditory feedback to users. In: Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems, pp. 2829–2836, (2016) https://doi.org/10.1145/2851581.2892420