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2025 Volume 3, Issue 3
Contemporary Education Frontiers
ISSN (Online): 3029-1860 ISSN (Print): 3029-1879

Design and Application of Haptic Feedback System for Virtual Characters based on Multimodal Perception

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Abstract: Improving the realism of tactile interaction of virtual characters has become a key bottleneck in the development of virtual reality technology, and multimodal perception fusion technology provides an innovative solution to break through this limitation. The physical simulation technology, based on the coupling of the virtual character's surface material, contact interaction and environment, realizes the calculation of tactile effects with high fidelity. At the same time, the haptic feedback system with multi-channel drive control ensures the coordination and unity of audio-visual and tactile three-dimensional perception.

Keywords: Multimodal perception; Virtual characters; Haptic feedback; Cross-modal fusion; Physical simulation

Online publication: April 26, 2025

1. Introduction

As the core carrier of digital interaction, the perceptual authenticity of virtual characters will directly affect the quality of user immersion experience, and the traditional virtual character system relies on a single visual presentation mode, due to the lack of deep perception support of the tactile dimension, resulting in an obvious lack of realism in human-computer interaction. The rise of multimodal perception technology has brought breakthrough solutions to the tactile interaction of virtual characters, and a more complete virtual character perception ecology can be built by integrating multi-dimensional perception channels such as vision, hearing, and touch. At present, the haptic feedback technology of virtual characters is facing core technical challenges, and the haptic feedback system of virtual characters based on multi-modal perception realizes the intelligent modeling of virtual character behavior and high-fidelity simulation of tactile attributes by establishing a cross-sensory information collaboration mechanism.

2. Fundamentals of virtual character modeling for multimodal perception mechanism

2.1. Multi-sensory information collection architecture for virtual characters

The multi-sensory information collection architecture of virtual characters builds a hierarchical and multi-dimensional perception data acquisition system, and realizes the three-dimensional spatial reconstruction of the visual characteristics of virtual characters by deploying high-resolution RGB-D camera arrays, in which the accuracy of the depth sensor can reach the millimeter level, which can capture the subtle differences in the changes of facial micro-expressions and body movements and posture transitions of virtual characters [1]. The voice interaction module adopts a multi-directional microphone array. It cooperates with the noise suppression algorithm to achieve the spatial accuracy of the virtual character's voice positioning in the horizontal direction of ± 3 degrees and the vertical direction of ± 5 degrees. The integrated voice emotion recognition engine can analyze the eight basic emotional states contained in the virtual character's intonation. The haptic sensing system uses a distributed network of pressure sensors, with a sensor density of 16 sampling points per square centimeter and a response frequency ranging from 1 Hz to 1000 Hz, which can detect physical parameters such as elastic modulus and roughness of the surface material of the virtual character, as well as temperature distribution.

2.2. Cross-modal data fusion of virtual character behavior

The cross-modal data fusion mechanism of virtual character behavior adopts a synchronization strategy that combines time series alignment and spatial registration, and solves the time synchronization problem between the visual frame rate of 30 fps, the audio sampling rate of 48 kHz and the update frequency of the tactile sensor of 1 kHz by establishing a unified timestamp reference system, and the time alignment accuracy is controlled within the range of ± 1 milliseconds. The spatial registration algorithm uses the three-dimensional coordinate transformation matrix to map the local coordinate systems of different sensors to the global coordinate system of the virtual character, and controls the registration error within ± 0.5 mm, the feature extraction module adopts the deep learning network architecture, the visual feature extraction uses the improved ResNet-101 network to extract the 512-dimensional feature vectors, the audio features use the Mel frequency cepstrum coefficient to extract the 39-dimensional acoustic features, and the tactile features extract the 64-dimensional texture features through wavelet transform analysis. The multimodal feature fusion adopts the neural network architecture weighted by the attention mechanism, and dynamically adjusts the weight coefficients of different modalities, with visual weights ranging from 0.3 to 0.6, auditory weights ranging from 0.2 to 0.4, tactile weights ranging from 0.1 to 0.5, and the comprehensive feature vector dimension after fusion is 256 dimensions.

3. Physical simulation technology for haptic feedback of virtual characters

3.1. Tactile modeling of virtual character surface materials

The use of haptic feedback technology is a viable and promising solution [2]. The tactile modeling of the surface material of the virtual character relies on a multi-level physical property description system, and the accurate simulation of different material types is achieved by establishing a database of material characteristics (**Figure 1**). Skin texture modeling uses fractal geometry theory, uses Perlin noise function to generate surface microscopic concave and convex structure, texture resolution reaches 0.01 mm accuracy to simulate the fine folds and pore distribution on the skin surface and sweat gland openings and other detailed features, clothing material modeling by measuring the elastic modulus of real fabrics, Poisson's ratio and density and other parameters, to establish a physical parameter library including cotton, silk and wool and other common materials, in which the elastic modulus of cotton material is set to 5–15MPa, silk material is set to 8–25MPa, leather material set 10–100MPa. The biological tissue modeling is based on the finite element method to construct a multi-level anatomical structure, covering the layered modeling of epidermal thickness of 0.1–0.2 mm, dermis thickness of 1–3 mm, and subcutaneous tissue thickness of 2–30 mm, and the Young's modulus of each layer is set to 0.1–0.2 MPa, 0.02–0.2 MPa, and 0.002–0.02 MPa, respectively.

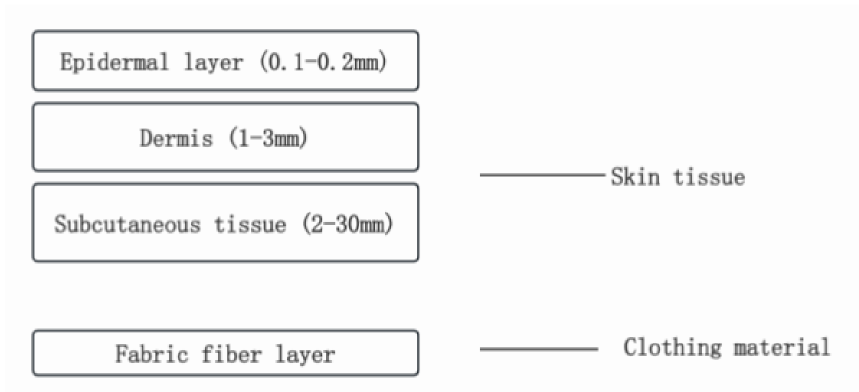

Figure 1. Material modeling hierarchy.

3.2. Mechanical calculations of virtual character contact interactions

Haptic feedback, as a form of tactile reproduction, is playing an increasingly important role in modern society [3]. The collision detection system uses the hierarchical enveloping box method to divide the surface of the virtual character into a triangular grid element with a minimum of 0.5 mm, and the detection frequency can reach 1000 Hz, which can capture instantaneous contact events and calculate the precise position of the contact point. The contact force calculation is based on Hertz's contact theory, considering the nonlinear properties of the material and the viscoelastic effect, and the normal contact force is calculated as follows:

$$F_n = K \times \ddot{a}^{\frac{3}{2}} + C \times \ddot{a} \tag{1}$$

Where K is the contact stiffness coefficient, δ is the contact deformation, C is the damping coefficient, and $\dot{\delta}$ is the deformation velocity. The tangential friction is based on the Coulomb friction model, and the friction coefficient μ is dynamically adjusted according to the material combination, with μ = 0.4–0.8 in skin-to-skin contact, μ = 0.2–0.6 in skin-fabric contact, and μ = 0.1–0.4 in skin-metal contact. The calculation of joint torque is based on the inverse dynamics algorithm, considering the mass distribution of the virtual character, the inertia matrix and the influence of gravity, the maximum torque of the shoulder joint is set to 40–60 Nm, the elbow joint is set to 20–40 Nm, and the wrist joint is set to 5–15 Nm.

3.3. Physical effects of virtual character environment coupling

The simulation of the physical effect of the coupling of the virtual character environment involves a variety of complex physical phenomena, and the real physical response is achieved by constructing a dynamic interaction model between the virtual character and the surrounding environment. The interactive modeling of scene objects uses the rigid body dynamics engine, which can support collision detection between virtual characters and static objects, the collision response time is controlled within 1 millisecond, the rebound coefficient is set according to the material combination, the rebound coefficient of wood surface is 0.3–0.5, the metal surface is 0.6–0.8, and the soft material is 0.1–0.3, and the environmental resistance simulation will consider the comprehensive effect of air resistance and surface friction, and the air resistance coefficient is set at 0.1–0.5 Ns/m. The surface frictional resistance is calculated dynamically based on the contact area and pressure, and the frictional resistance ranges from 0.5 to 5.0 N. The thermal conductivity coefficient is set at 0.2–0.6 W/(mK) and the specific heat capacity is set at 3000–4000 J/(kgK), which can simulate the temperature change at the moment of contact, with a temperature transfer rate of 0.5–2.0 degrees per second.

4. Architecture of haptic feedback system based on multimodal perception

4.1. Generation and encoding of multimodal tactile signals

The generation and encoding of multi-modal tactile signals use perceptual fusion algorithms to convert visual, auditory and tactile three-dimensional information into unified tactile feedback signals. The visually-guided tactile signal mapping is based on depth image analysis, and the pixel depth value is converted into tactile intensity parameters by extracting the surface geometric features of the convolutional neural network, and mapping function is:

$$I_{tactile} = \alpha \times \log(d_{visual} + 1) \times \beta \times \nabla^2(d_{visual}) \quad (2)$$

Where $I_{tactile}$ is tactile intensity, d_{visual} is the visual depth value, α and β are the weight coefficients, and ∇^2 is the Laplace operator.

The auditory-assisted tactile modulation mechanism analyzes the characteristics of the audio spectrum and maps the sound intensity, frequency and timbre to the tactile vibration mode, where the low-frequency sound, i.e., the sound of 20–200 Hz, will be mapped as the low-frequency vibration, the medium-frequency sound, that is, the sound of 200–2000 Hz, will be mapped as the pulsed haptics, and the high-frequency sound, that is, the sound of 2000–20000 Hz, will be mapped as the fine texture perception. The tactile pattern recognition with multi-sensory fusion uses Bayesian classifiers to learn the multi-modal feature combinations of different materials through training samples, and its recognition accuracy can reach more than 92%, and the response delay can be controlled within 5 milliseconds.

4.2. Multi-channel drive control of haptic feedback devices

The multi-channel drive control system of the haptic feedback device is based on a distributed actuator array to achieve multi-point synchronous tactile stimulation output. The actuator configuration adopts an 8 × 8 grid layout, the size of a single actuator is 5 × 5 mm, the driving frequency range covers 1–300Hz, the maximum output force is 2 N, and the displacement accuracy reaches 0.01 mm, and the parallel excitation scheme adopts time-division multiplexing technology, which divides 64 actuators into 8 groups, each group of 8 actuators is driven at the same time, and the cycle period is 1 millisecond to ensure the continuity of user perception. The delay compensation algorithm adopts the predictive control mechanism, predicts the contact time by analyzing the user's hand movement trajectory, triggers the actuator response 0.5–2 milliseconds in advance, compensates for the inherent delay of the system, and the nonlinear correction adopts the look-up table method, and dynamically corrects the saturation characteristics of the actuator and non-ideal factors such as hysteresis effect and temperature drift, with a correction accuracy of more than 95%, and the controller adopts ARM Cortex-M7 processor, with a running frequency of 168 MHz and a built-in floating point operation unit. It supports real-time signal processing, and the communication interface adopts USB 3.0 protocol, and the data transmission rate reaches 5 Gbps.

4.3. User-oriented haptic experience adaptive mechanisms

The user-oriented adaptive mechanism of haptic experience relies on the establishment of individual difference models to achieve personalized optimization of haptic feedback [4]. The test range covers 0.01–2.0 N force stimulation and 0.1–10 μm displacement stimulation and 1–1000 Hz vibration stimulation, the calibration accuracy can reach ± 5% of the perception threshold, the physiological monitoring module integrates a variety of physiological signal acquisition devices such as heart rate sensor, skin conductivity sensor and electromyography sensor, etc., which can monitor the user's fatigue state in real time. Heart rate variability can be analyzed with an accuracy of 1 millisecond, skin conductivity measurement ranges from 0.1 to 100 μS, and EMG signal frequency response ranges from 10 to 500 Hz. The subjective evaluation system adopts a multi-dimensional scale design, including comfort score (1–10 points), realism score (1–10 points) and fatigue score (1–10 points) and other indicators, and the personalized tactile preference model is established by analyzing user evaluation data through machine learning algorithms, with a prediction accuracy of more than 85%, and the adaptive adjustment strategy dynamically adjusts the haptic feedback parameters according to physiological monitoring data and subjective evaluation results.

5. Application verification of multimodal virtual character haptic system

5.1. System performance evaluation

The performance evaluation of the multi-modal virtual character haptic feedback system uses a multi-dimensional quantitative testing system to comprehensively verify the effectiveness of the system by combining objective performance index measurement and subjective experience evaluation. The haptic feedback accuracy test is based on the high-precision force sensor, measuring the deviation between the output and the theoretical value of the system, covering the force sensing range of 0.1–10 N and the frequency range of 1–1000 Hz and the displacement range of 0.01–5 mm, the accuracy is controlled within ± 2.8%, the multi-modal perception delay test is triggered by synchronous triggering of visual auditory tactile stimulation, and the time difference between each modality is measured with a high-speed camera and an oscilloscope, and the overall delay is controlled within 15 milliseconds. The user experience evaluation uses a standardized questionnaire survey, recruits 50 test users to carry out a two-week use test, the evaluation indicators cover the dimensions of immersion, realism, comfort, ease of use, etc., and the system stability test has achieved 99.7% through continuous 72 hours of uninterrupted operation, monitoring key parameters such as the number of system crashes, memory leaks, and processor temperature. The system core performance test results are as shown in **Table 1**.

Table 1. System core performance test results

Test metrics	Actual results	Design goals	Attainment status
Haptic feedback accuracy	± 2.8%	± 3.0%	✓
System response delay	15 ms	≤ 20 ms	✓
Feature fusion accuracy	92.3%	≥ 90%	✓
User immersion scores	8.4	≥ 7.5	✓
System availability	99.7%	≥ 99 %	✓
Actuator output force	1.98 N	≥ 2.0 N	△

Note: ✓ indicates that the standard is met, and △ indicates that the target is close to the standard

As can be seen from the test results, the system meets or exceeds the design target on most performance metrics. Among them, the core indicators such as haptic feedback accuracy, system response delay and user experience evaluation are excellent, which verifies the effectiveness of the multi-modal perception fusion architecture, and the maximum output force of the actuator is slightly lower than the design target, but it is still within the acceptable range and does not affect the overall performance of the system.

5.2. Application field expansion

The multimodal virtual character haptic feedback system has the potential to be widely used in many technical fields and can provide important technical support for the digital transformation of different industries. In the field of medical rehabilitation, virtual characters can be used to guide patients through rehabilitation training, and to help patients rebuild motor function with precise tactile feedback, and in the medical field, haptic feedback devices are often used to improve the quality of life of people with disabilities due to their lightweight and good compliance [5]. In the field of entertainment interaction, the tactile interaction ability of virtual characters can significantly improve the immersive experience of users, and create a more realistic virtual environment in applications such as virtual reality games, social platforms and digital art displays, and the field of industrial design can realize the virtual verification of product prototypes with the help of the haptic feedback function of virtual characters, which can reduce the cost of physical prototype production and improve design efficiency, and the research field of human-computer interaction provides an experimental platform for exploring new interaction modes and promotes the sustainable development of tactile interaction technology.

6. Conclusion

The haptic feedback system of virtual characters based on multi-modal perception has successfully built an immersive interactive environment with three-dimensional collaboration of audio-visual touch, which has significantly improved the authenticity of virtual character perception. The cross-modal data fusion algorithm effectively integrates the multi-dimensional perception information of the virtual character, the adaptive perception model realizes the intelligent evolution process of the virtual character's behavior, and the physical simulation technology lays a solid foundation for high-fidelity haptic feedback by accurately modeling the material attributes and contact interaction and environmental coupling effects of the virtual character. The parallel drive control mechanism of the multi-channel haptic feedback system ensures the real-time and accurate transmission of tactile signals, and the personalized experience optimization strategy meets the differentiated needs of different users.

Funding

2024 Wenzhou Science and Technology Bureau Basic Scientific Research Project, "Research on the Application of Multimodal Haptic Technology in Virtual Character Interaction Design" (Project No. G20240079)

Disclosure statement

The author declares no conflict of interest.

References

[1] Ma X, Tong Q, Li Y, et al., 2022, Research on the Construction of Intelligent Design Tactile Experiences Based on Multi-Modal Tactile and Pseudo-Tactile Feedback. Decoration, 2022(9): 28–33.

[2] Sun Y, Zeng H, Zhang J, et al., 2025, Human-Multi-Robot Team Member Perception Enhancement Based on Multimodal Haptic Feedback. Journal of Ordnance Equipment Engineering, 46(1): 267–276.

[3] Dong Z, 2024, Research on Pressure-Temperature Dual-Mode Flexible Haptic Feedback Device, thesis, Hangzhou Dianzi University.

[4] Wang M, Shi J, 2022, Virtual Reality Interaction Technology of Visual Hand Based on Haptic Feedback. Information and Computer (Theoretical Edition), 34(17): 20–23.

[5] Ma X, Tong Q, Li Y, et al., 2022, Research on the Construction of Intelligent Design Tactile Experiences Based on Multi-modal Tactile and Pseudo-tactile Feedback. Decoration, 2022(9): 28–33.