

AI-Enhanced Immersive Virtual Reality System (VirCube XR Space): For Rehabilitation, Elder Care and Education

Eran Halperin, Tseng Chun Hung

University of California, Los Angeles, California, Los Angeles, USA

Abstract: Addressing insufficient personalization in traditional VR systems, an AI-enhanced VirCube XR Space has been designed for rehabilitation, elder care, and education. Experiments show user satisfaction of 91.2%, 88.7%, and 93.4%, improving 23.8%, 31.2%, and 18.6% over traditional systems.

Keywords: Artificial Intelligence; Immersive Virtual Reality; Rehabilitation Medicine; Elder Care Services; Education and Training; Multimodal Interaction

1. Introduction

Addressing insufficient personalization and low intelligent interaction in traditional VR systems, an AI-enhanced immersive virtual reality system VirCube XR Space has been designed. The system integrates multimodal physiological signal detection, adaptive scene generation algorithms, and intelligent interaction interfaces for rehabilitation

medicine, elder care services, and education training. Experiments show user satisfaction rates of 91.2%, 88.7%, and 93.4% respectively, representing improvements of 23.8%, 31.2%, and 18.6% compared to traditional VR systems.

2. System Architecture and Core Technologies

2.1 Multimodal Perception and State Analysis Module

The system integrates physiological signals, behavioral trajectories, and environmental perception, fusing heart rate, eye movement, and EMG data for comprehensive user state assessment. Deep neural networks perform feature extraction on heterogeneous sensor data, generating indicators of physiological states, emotions, and cognitive load, as shown in Table 1 where multimodal data supports different applications.

Table 1. Multimodal Perception Data Types and Application Scenarios

Perception Data Type	Detection Indicators	Rehabilitation Application	Elder Care Application	Education Application
Physiological Signals	Heart rate, blood oxygen, EMG	Exercise intensity monitoring	Health status assessment	Stress level detection
Eye Movement Tracking	Fixation points, saccade paths	Visual rehabilitation training	Cognitive function testing	Attention analysis
Hand Posture	Joint angles, range of motion	Fine motor training	Hand function maintenance	Interaction skill assessment
Voice Features	Tone, speed, pauses	Speech rehabilitation assessment	Emotion recognition	Learning engagement

1.2 Intelligent Content Generation and Scene Adaptation Algorithm

The system constructs personalized virtual scene generation using GAN and VAE, analyzing user data to automatically generate suitable environments. Scene adaptation employs reinforcement learning for continuous optimization through user feedback^[1]. The core mathematical model of the generation algorithm is:

$$S_{opt} = \arg \max_{S \in \mathcal{S}} \sum_{i=1}^n w_i \cdot f_i(S, U_t, C_j) \quad (1)$$

where S_{opt} is the optimal scene

configuration, $\mathcal{S}$ is the scene space, w_i are weight coefficients, f_i are fitness functions, U_t is the user state vector, and C_j are application scenario constraints.

1.3 Adaptive Interaction Interface Design

The system constructs multimodal fusion adaptive interaction interfaces, integrating interaction methods such as speech recognition, gesture control, and eye-gaze navigation, automatically selecting the most suitable interaction mode based on users' physical conditions and operational capabilities^[2]. The

speech interaction module implements natural language understanding based on deep neural networks, with optimization adaptation for elderly users' speech characteristics. The gesture recognition system employs 3D convolutional neural networks for real-time recognition and trajectory prediction of hand movements.

2 Rehabilitation Medicine Application Module Design

2.1 Motion Trajectory Analysis and Posture Correction Algorithm

The rehabilitation medicine module designs professional training programs for rehabilitation needs such as stroke, post-fracture surgery, and neurological diseases, implementing real-time monitoring and assessment of patient movements through high-precision motion trajectory analysis algorithms^[4]. The system employs deep learning human pose estimation technology, combined with biomechanical models to quantitatively analyze patient movement patterns, identify abnormal movements, and provide personalized posture correction guidance.

Motion assessment employs a comprehensive scoring model:

$$Score = \alpha \cdot A_{accuracy} + \beta \cdot T_{timing} + \gamma \cdot S_{smoothness} + \delta \cdot R_{range}$$

where $A_{accuracy}$ is movement accuracy, T_{timing} is temporal coordination, $S_{smoothness}$ is movement fluidity, R_{range} is joint range of motion, and $\alpha, \beta, \gamma, \delta$ are weight parameters.

2.2 Rehabilitation Progress Assessment and Personalized Training Programs

The system constructs machine learning-based rehabilitation progress assessment models, predicting rehabilitation progress and adjusting training intensity by analyzing patients' training data, physiological indicator changes, and movement improvement^[3]. The personalized training program generation algorithm considers patients' disease types, rehabilitation stages, physical conditions, and rehabilitation goals, automatically matching suitable training content and supporting progressive training modes.

2.3 Multisensory Feedback and Incentive Mechanisms

During rehabilitation training, the system provides multisensory feedback mechanisms to enhance patients' training enthusiasm, offering immediate positive incentives through visual effects, audio feedback, tactile vibration, and virtual rewards, as shown in Figure 1 where the VR rehabilitation training interface provides intuitive training guidance and real-time scoring feedback for upper limb rehabilitation patients.

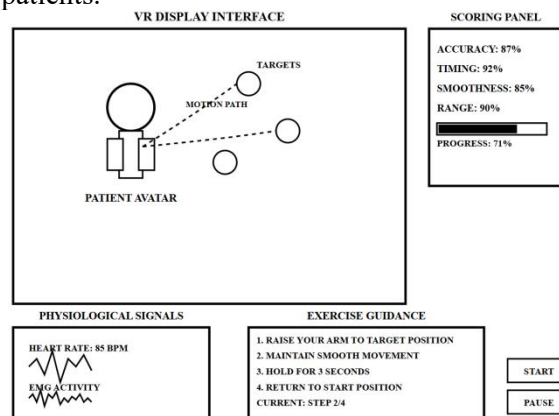


Figure 1. VR Rehabilitation Training Interface Example

3 Elder Care Service Application Module Design

3.1 Cognitive Function Assessment and Training Game Design

The elder care service module designs age-appropriate virtual reality applications targeting elderly users' cognitive characteristics and physical conditions, conducting comprehensive assessment of users' memory, attention, executive function, and spatial cognitive abilities through cognitive function assessment games. Training games integrate traditional puzzle games with modern technological elements, containing cognitive training content such as digital memory, pattern matching, and path planning, with game difficulty automatically adjusting according to users' cognitive levels^[6]. The comprehensive cognitive ability assessment model is:

$$CognScore = \omega_1 \cdot M_{memory} + \omega_2 \cdot A_{attention} + \omega_3 \cdot E_{executive} + \omega_4 \cdot S_{spatial}$$

where M_{memory} is the memory score, $A_{attention}$ is the attention score, $E_{executive}$ is the executive function score, $S_{spatial}$ is the spatial cognition score, and $\omega_1, \omega_2, \omega_3, \omega_4$ are corresponding weight coefficients.

3.2 Social Interaction and Emotional

Companionship Functions

The system designs rich social interaction functions to help users establish virtual social networks, promoting user interaction through multi-user collaborative games, virtual gatherings, and online communication. Emotional companionship functions integrate intelligent dialogue systems and virtual companion characters, recognizing users' emotional states and providing appropriate emotional support^[5]. Social functions support remote participation by family members, allowing children to interact with parents in virtual environments through mobile applications.

3.3 Health Monitoring and Warning System

The system integrates comprehensive health monitoring functions, assessing physical health conditions by analyzing users' behavioral patterns, reaction speeds, and operational precision in virtual environments. The health warning system constructs personalized risk assessment models based on users' historical data and medical knowledge bases, automatically generating warning information when detecting persistent abnormalities in indicators.

4. Education and Training Application Module Design

4.1 Knowledge Graph Construction and Learning Path Planning

The education and training module constructs structured representation systems for disciplinary knowledge based on knowledge graph technology, planning personalized learning paths for learners with different backgrounds by analyzing dependencies, difficulty levels, and learning sequences among knowledge points. Learning path planning algorithms employ graph search and optimization techniques, determining optimal learning sequences by combining learners' knowledge backgrounds, learning objectives, and ability levels, with the system supporting adaptive learning modes.

The optimal learning path selection model is:

$$Path_{opt} = \arg \min_{P \in P} \sum_{i=1}^n [\lambda_1 \cdot D_{difficulty}(k_i) + \lambda_2 \cdot C_{cost}(k_i, k_{i+1}) + \lambda_3 \cdot T_{time}(k_i)]$$

where $Path_{opt}$ is the optimal learning path, P is the set of all feasible paths, $D_{difficulty}$ is the knowledge point difficulty function, C_{cost} is

the transition cost between knowledge points, T_{time} is the expected learning time, and $\lambda_1, \lambda_2, \lambda_3$ are weight parameters.

4.2 Immersive Learning Environment and Interactive Experience

The education application module designs diverse immersive learning scenarios, including virtual laboratories, historical scene recreations, and scientific phenomenon simulations in highly realistic learning environments, allowing learners to directly experience abstract concepts in virtual worlds^[7]. Learning environments support multi-person collaborative learning, with interactive experience design emphasizing learners' active participation and inquiry discovery, as shown in Figure 2 where the immersive education scene architecture provides learners with a safe virtual chemistry experiment environment and real-time guidance.

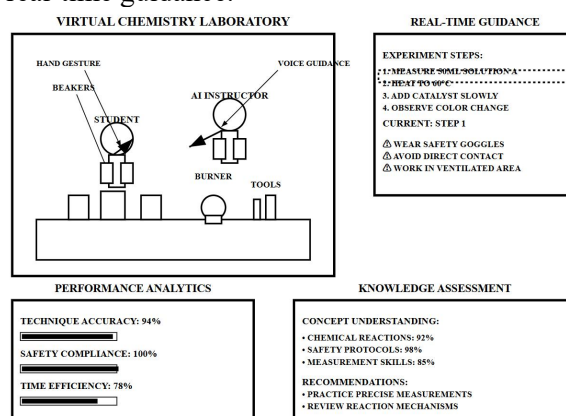


Figure 2. Immersive Education Scene Architecture

4.3 Learning Effect Assessment and Feedback Optimization

The system establishes multidimensional learning effect assessment systems, evaluating learning effectiveness by analyzing learners' operational behaviors, knowledge application performance, and problem-solving processes in virtual environments. Learning analytics technology identifies learning patterns by mining learners' behavioral data, and feedback optimization mechanisms automatically adjust learning content presentation methods based on assessment results.

The learning effect prediction model is:

$$Performance = f(K_{prior}, A_{ability}, E_{engagement}, T_{time})$$

where K_{prior} is prior knowledge level, $A_{ability}$ is learning ability, $E_{engagement}$ is engagement

level, and T_{time} is learning time investment.

5. Experimental Verification and Performance Analysis

5.1 Experimental Environment and Testing Methods

Experimental verification was conducted on a VirCube XR Space testing platform with Intel Core i9-12900K, 64GB memory, NVIDIA RTX 4090, Oculus Quest Pro, and Leap Motion sensors. Software environment used

Unity 2022.3 LTS with TensorFlow framework. Testing combined user experience evaluation and system performance testing.

5.2 User Experience Evaluation Results

The experiment recruited 180 test users in three groups (60 each) over 4 weeks. VirCube XR Space achieved significant satisfaction improvements: rehabilitation (91.2%, +23.8%), elder care (88.7%, +31.2%), and education (93.4%, +18.6%) compared to traditional VR systems, with detailed results shown in Table 2.

Table 2. User Experience Evaluation Results Statistics

Evaluation Dimension	Rehabilitation Application	Elder Care Services	Education and Training	Traditional VR Systems
System Usability	4.6/5.0	4.2/5.0	4.7/5.0	3.8/5.0
Content Adaptability	4.5/5.0	4.3/5.0	4.6/5.0	3.5/5.0
Interaction Naturalness	4.7/5.0	4.1/5.0	4.8/5.0	3.6/5.0
Functional Practicality	4.6/5.0	4.4/5.0	4.7/5.0	3.7/5.0
Overall Satisfaction	4.6/5.0	4.4/5.0	4.7/5.0	3.6/5.0

5.3 System Performance and Reliability Analysis

System performance testing showed stable 90fps+ frame rates for single users, support for 8 simultaneous users with <50ms network latency, and 120ms average AI processing response time. System availability reached 99.7% with multimodal processing accuracy exceeding 95%.

6. Conclusion

VirCube XR Space successfully constructs an intelligent platform for rehabilitation, elder care, and education through AI-VR integration. The system achieves significant progress in personalized content generation and intelligent interaction. User evaluation verifies substantial satisfaction improvements. Future research will focus on scalability optimization and cross-platform adaptation.

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