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Original Paper

Design and Application of Airport Barrier-free Guide System Based on Virtual Reality Technology

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Abstract

The Civil Aviation Administration of China (CAAC) has introduced a series of policies on airport accessibility infrastructure, which has clarified the direction for upgrading airport accessibility services and created urgent demands for the development and implementation of intelligent accessibility devices. Currently, most domestic airports still face challenges in accessibility design, including reliance on traditional facilities, lack of smart navigation systems, insufficient coverage in complex areas, and difficulties in adapting to the personalized travel needs of visually impaired passengers. These issues significantly impact the efficiency and experience of airport travel for the visually impaired community. The rapid development of virtual reality (VR) technology, with its capabilities in high-fidelity scene replication, immersive interactive perception, and precise spatial modeling, provides critical technical support for overcoming bottlenecks in airport accessibility smart device development. This holds significant practical value for enhancing the scene adaptability and user-friendliness of accessibility devices. Based on this, this paper focuses on airport accessibility guidance as a core application scenario, conducting research on the design and application of VR-integrated guidance systems. The study defines core system requirements and design principles, completes hardware selection and software module development, and validates system performance through scenario simulation tests. The research confirms that this VR-guided system effectively addresses pain points in existing airport accessibility services, aligns with CAAC's policy requirements, and creates safe, efficient, and convenient travel paths for visually impaired passengers. It also provides a practical model for technological innovation and application implementation of accessibility smart devices in the transportation sector.

Keywords
virtual reality technology, airport accessibility, guide system, special passenger service

1. Introduction

1.1 Research Background

With the high-quality development of China's civil aviation industry and continuous upgrades in public service capabilities, safeguarding the travel rights of special passengers has become a key focus for improving service quality and efficiency. Policy documents such as the "Civil Airport Management Regulations" and "Airport Barrier-Free Facilities Design Specifications" have set clear requirements for barrier-free airport infrastructure, emphasizing the need to fully consider the travel needs of special groups including the elderly, disabled, pregnant women, children, and the visually impaired, ensuring airports provide convenient and safe services. These policies outline the development direction of standardized and intelligent barrier-free services, compelling airports to address service gaps for special passengers. This initiative effectively safeguards the rights of visually impaired, hearing-impaired, and other special groups to safe, convenient, and dignified civil aviation travel, while providing concrete guidelines and actionable directions for enhancing the airport barrier-free service system.

Meanwhile, the travel needs of special passengers—particularly blind travelers—have become increasingly precise, personalized, and efficient. They demand comprehensive services covering the entire airport journey from check-in, security screening, and waiting to boarding, including route navigation, facility location, and emergency alerts. However, current accessibility services at most airports still fall short: traditional facilities dominate, smart guide devices are underutilized, and complex transfer zones or remote boarding gates often lack navigation guidance. Most responses remain passive, relying on manual coordination rather than proactive, tailored services. This fails to meet blind travelers' core needs for autonomous mobility and efficient passage. Moreover, service processes are disconnected from actual requirements, resulting in low efficiency and poor experiences for blind passengers. The growing imbalance between supply and demand has become a critical bottleneck hindering service quality upgrades at airports.

Amid the wave of technology empowering public welfare, virtual reality (VR) technology has achieved rapid iteration through core advantages including high-fidelity 3D scene replication, precise spatial positioning, and immersive interactive perception. Its applications in spatial navigation, scenario simulation, and auxiliary perception have become increasingly mature, breaking through the technical limitations of traditional barrier-free guide devices. VR can digitally reconstruct the entire physical airport environment, providing blind passengers with real-time, accurate route guidance and environmental alerts. This offers innovative technical solutions and creative approaches to address challenges in airport special passenger services. Against this backdrop, how to leverage VR technology in alignment with the Civil Aviation

Administration's policy requirements, specifically addressing gaps in existing airport barrier-free services for special passengers, and building an airport barrier-free guide system tailored to blind travelers' needs has become a critical research focus in smart airport development and special passenger rights protection. It also represents a key pathway to enhancing the inclusiveness and accessibility of civil aviation services.

1.2 Research Objective

This study focuses on developing an airport accessibility guidance system integrated with virtual reality technology. Aligned with the Civil Aviation Administration's policies on barrier-free infrastructure and special passenger services, the research addresses existing gaps in accessibility services for blind travelers and other special passengers. By defining core development directions and design principles, the project establishes a comprehensive architecture and functional modules for a full-process airport accessibility system. The study validates the applicability and value of virtual reality technology in this context, aiming to enhance smart accessibility services, improve travel autonomy and convenience for blind passengers, and provide actionable technical solutions for refined special passenger services and intelligent upgrades of barrier-free facilities. Furthermore, it offers theoretical support and practical references for advancing virtual reality applications in civil aviation's special passenger service sector.

1.3 Research Significance

1.3.1 Theoretical Significance

This study bridges the intersection of civil aviation accessibility services and virtual reality technology, focusing on airport accessibility guidance for the visually impaired. It enriches the theoretical framework for special passenger services in the context of smart aviation, effectively addressing the academic gap where existing research predominantly focuses on traditional accessibility infrastructure while rarely integrating emerging virtual reality technologies for specialized airport guidance systems. The study clarifies the compatibility logic and application pathways of virtual reality technology in airport accessibility guidance, establishing a design framework for a seamless guidance system tailored to airport workflows. This provides a novel research perspective and theoretical reference for future explorations of virtual reality applications in civil aviation special passenger services, while also laying a solid foundation for theoretical research on accessible intelligent devices in transportation. Ultimately, it enhances the theoretical system of integrating accessibility services with digital technologies.

1.3.2 Practical Significance

This study aligns with the Civil Aviation Administration's policy directives to advance airport accessibility infrastructure and enhance services for special passengers. It specifically addresses practical challenges in current airport services for blind travelers, including insufficient navigation accuracy, lack of intelligent support systems, and incomplete service coverage throughout the entire process. The designed airport accessibility guidance system integrated with virtual reality technology can effectively improve the autonomy, safety, and convenience of blind travelers' airport experiences, ensuring equal travel rights for special groups while demonstrating significant social value. The implementation of this system will help airports optimize service processes for special passengers, reduce manual service costs, and facilitate the intelligent and refined upgrading of accessibility services, accelerating the universalization of smart airport development. Additionally, the research findings provide replicable and scalable practical models for upgrading accessibility and intelligent services at other transportation hubs such as high-speed railway stations and major passenger terminals, offering valuable references for the digital transformation of accessibility services in the industry. This study holds strong application and promotion value for the sector.

2. Application Basis of Virtual Reality Technology in Airport Barrier-free Guide System

2.1 Application Principle of Virtual Reality Technology in Airport Barrier-free Guidance

The application of virtual reality technology in airport barrier-free guidance systems is fundamentally based on four core technological capabilities: 3D modeling, immersive perception, real-time interaction, and spatial positioning. By digitally reconstructing and intelligently interpreting airport physical spaces, this technology follows a logical pathway where "virtual scenes map real-world environments, technological perception replaces visual perception, and precise command delivery transmits navigation information." This creates a safe, accurate, and efficient travel assistance bridge for blind passengers. The core application principles are progressively realized through four dimensions: digital reconstruction of scenarios, multimodal perception substitution, real-time spatial navigation, and intelligent interactive feedback, as detailed below:

First, the principle of airport-wide digital reconstruction serves as the foundational premise for implementing barrier-free guidance systems. This principle utilizes the airport's physical space as a blueprint, employing technologies like laser scanning and real-scene modeling to digitally replicate all areas at a 1:1 scale. This includes terminal buildings, check-in zones, security checkpoints, waiting halls, boarding gates, transit corridors, restrooms, and accessibility facilities. The process accurately reconstructs spatial dimensions, layouts, facility locations, and movement paths, creating a virtual twin scenario synchronized with the actual airport in real time. Simultaneously, dynamic elements within the airport (such as temporary boarding gate changes, corridor congestion, or facility maintenance) are integrated with real-time data and updated in the virtual environment. This ensures high consistency between the virtual and physical spaces, providing precise digital references for navigation guidance and environmental perception. This approach effectively addresses the core challenge of traditional guidance methods failing to accurately represent complex airport spatial layouts.

Secondly, the multimodal perception substitution and information translation principle forms the core logic for adapting to blind passengers 'visual limitations. To address the pain point of blind travelers' inability to obtain environmental information through visual means, virtual reality technology centers on "non-visual perception" to achieve multimodal translation and transmission of environmental information. The core principle involves converting spatial information, facility details, and warning signals in virtual environments into perceptible forms for blind individuals through technical processing. Firstly, voice synthesis technology transforms path guidance, facility locations, and real-time alerts into clear and concise voice broadcasts. Secondly, tactile feedback technology utilizes vibration modules on guide glasses to deliver directional, distance, and obstacle warnings through varying frequencies and intensities. Thirdly, spatial audio technology employs 3D surround sound to achieve "sound source localization," assisting blind passengers in determining target directions. This creates a multimodal perception system integrating "voice + tactile + audio" that precisely translates visual information into perceptible data, enabling efficient transmission of environmental information.

Third, the real-time precision spatial navigation and path planning principle serves as the core support for ensuring efficient passage of blind passengers. This principle integrates virtual reality technology's spatial positioning capabilities with path algorithm optimization techniques to establish a dynamic navigation system. On one hand, the positioning module in guide glasses captures the real-time coordinates of blind passengers in physical airports and synchronously maps them to virtual twin scenarios, achieving precise correspondence between "real locations and virtual coordinates" while keeping positioning errors within safe passage thresholds. On the other hand, the system automatically plans optimal barrier-free routes based on spatial data in virtual environments, considering passengers' final destinations (e.g., check-in counters, boarding gates), avoiding unsuitable areas like staircases and narrow passages, and prioritizing accessible elevators and dedicated channels. Simultaneously, the system dynamically updates path information in virtual scenarios in response to airport changes (e.g., temporary traffic control, crowd congestion), adjusting navigation plans in real time and providing feedback to passengers. This ensures dynamic, precise, and barrier-free navigation throughout the entire "start-to-destination" process, guaranteeing both efficiency and safety in passage.

Fourth, the principle of intelligent interaction feedback and demand adaptation serves as the cornerstone for enhancing system usability and adaptability. Centered on the practical needs of blind travelers, this principle establishes a two-way intelligent interaction mechanism between passengers and the system. Blind travelers can conveniently submit requests (such as locating restrooms, inquiring about boarding gate information, or seeking emergency assistance) through voice commands or simple touch inputs. The system captures these signals via voice recognition and touch sensing technologies, swiftly retrieves relevant information in virtual environments, and provides feedback. Simultaneously, the system continuously collects user data (including travel speed, stop points, and feedback) while integrating environmental data from virtual scenarios. This enables continuous optimization of route planning logic, information delivery methods, and interaction response speed, creating a closed-loop operation of "demand triggering → intelligent response → data feedback → optimization upgrade." This ensures the system consistently adapts to the personalized travel needs of blind travelers, thereby improving the precision and convenience of guided services.

2.2 Analysis of the Requirements of Virtual Reality Technology in Airport Barrier-Free Guide Systems

By integrating virtual reality technology principles with airport accessibility requirements, the system focuses on three core aspects: functional adaptation, technical performance, and user experience. Functionally, it must digitally replicate and dynamically update all airport scenarios, enabling multimodal information translation through precise voice and tactile feedback to convey path, obstacle, and facility details. Technically, it requires accurate spatial positioning and real-time navigation, adapting to dynamic environments like crowd movements and facility changes while maintaining low-latency interaction. For users, the system should align with blind operational habits, support voice commands, and feature lightweight, comfortable, and long-lasting devices to ensure stable reliability throughout the travel process, effectively meeting visually impaired passengers' needs for autonomous and safe mobility.

3. Hardware Design of Airport Barrier-Free Guide System with Virtual Reality Technology

3.1 Selection of Hardware Equipment

To address the core accessibility needs of airport navigation for the visually impaired and leverage virtual reality technology, the hardware selection prioritizes precision, portability, and stability while balancing practicality and compatibility. The core solution features lightweight VR guide glasses as the terminal device, with models equipped with high-definition panoramic cameras and LiDAR for accurate airport scene scanning and 3D modeling. These glasses integrate high-precision UWB positioning modules that work with indoor positioning base stations to achieve centimeter-level real-time tracking, effectively eliminating navigation blind spots. The system also incorporates multimodal feedback components including bone conduction headphones and micro-vibration motors, ensuring clear voice announcements without disrupting environmental perception or providing precise tactile cues. Additionally, the design employs long-lasting low-power batteries and anti-interference chips to withstand prolonged use in complex electromagnetic environments, meeting the essential requirements for efficient passage of visually impaired passengers.

All selected hardware complies with accessibility standards, balancing operational convenience and durability. Core modules prioritize low-power, high-light-resistant models to adapt to diverse scenarios like airport terminals and enclosed security checkpoints. The devices feature expandable interfaces for future integration with smart airport platforms, providing hardware support for system upgrades while addressing both immediate practical needs and long-term scalability.

3.2 Hardware Integration Solution

The system's hardware integration adopts a distributed architecture of "core terminal + auxiliary modules + linked base stations", enabling efficient device coordination and data interoperability. The core seamlessly integrates positioning modules, sensing modules, and feedback components into VR guide glasses terminals, reducing device size while ensuring comfortable wearability and operational convenience for single-handed operation by visually impaired users. Auxiliary modules feature external portable charging ports for battery replenishment, paired with emergency call buttons to facilitate rapid assistance in critical scenarios. By linking airport indoor positioning base stations with scene data terminals, the system establishes a comprehensive data transmission network that enables real-time synchronization between glasses terminals and airport backend systems, ensuring instant response to scene updates and route adjustments. The integration simultaneously optimizes hardware compatibility and anti-interference capabilities, mitigating equipment failures in complex airport environments to ensure stable system operation.

The integrated system employs modular assembly design to reduce maintenance and replacement costs. It features a built-in fault self-diagnostic module that monitors hardware status in real time, providing tactile alerts for anomalies to enhance fault tolerance. The hardware layout is optimized with core components concentrated on the inner frame of the glasses, ensuring both balance and concealment during wear. This design prevents bulky equipment from hindering mobility for visually impaired passengers, perfectly aligning with the practical needs of barrier-free travel throughout the entire journey.

4. Software Design of Airport Barrier-free Guide System with Virtual Reality Technology

4.1 Software Functional Module Design

Aligned with the core accessibility requirements for airport guidance systems, this solution leverages virtual reality technology principles to decompose the software into four functional modules with clearly defined roles and seamless integration. The first module, Scene Modeling, enables 3D digital replication and real-time updates of the entire airport area, synchronizing critical data including accessibility facilities and movement restrictions. The second, Precision Navigation, integrates route planning and real-time positioning to automatically generate optimal accessible paths while dynamically adjusting for unexpected situations. The third, Multimodal Interaction, translates spatial information into voice and tactile feedback formats tailored to blind users' preferences. The fourth, Emergency Support, provides one-touch assistance, anomaly alerts, and emergency route reconstruction. Designed with lightweight operation and low-latency response, each module balances functional completeness with user-friendliness, precisely meeting the full-process travel needs of visually impaired passengers in airports.

Each functional module features dedicated iteration interfaces, allowing targeted upgrades and optimizations without requiring full system reconstruction, which significantly reduces maintenance costs. The modular design is fully optimized for visually impaired users, streamlining interaction layers and eliminating redundant steps. Core functions can be activated with a single voice command, ensuring seamless operation for users of all proficiency levels and maximizing the software's accessibility and adaptability.

4.2 Software Functional Module Integration Solution

The system software adopts a modular collaborative integration architecture, with data interoperability as its core and process linkage as its foundation, achieving seamless integration and efficient operation of four functional modules. A unified data platform serves as the integration core, breaking down data barriers between modules such as scenario modeling and precision navigation, enabling real-time sharing of airport spatial data, positioning data, and feedback data. Following the travel logic of "scenario perception-path planning-information translation-emergency fallback", the system establishes module linkage trigger mechanisms to ensure coherent coordination in generating navigation instructions, synchronizing multimodal feedback, and responding to emergencies. Simultaneously, it optimizes operational power consumption and response speed after module integration, streamlines redundant interaction processes, and adapts to the hardware terminal's operational capacity. This ensures the integrated software system operates with simplicity and stability, rapidly addressing various travel needs of visually impaired passengers while enhancing the accuracy and fluidity of airport barrier-free guide services.

After integration, the system synchronously deploys software operation monitoring and fault-tolerant mechanisms to track real-time status of all modules. Should any module fail, it automatically switches to backup solutions, preventing system-wide paralysis that could disrupt travel services. Leveraging the data platform, it performs real-time aggregation and analysis of operational data. By analyzing user behavior data, the system identifies areas for module optimization, forming a closed-loop system of "integrated operation-data feedback-iterative optimization" to continuously enhance the software's operational stability and service precision.

5. Performance Testing of Airport Barrier-Free Guide Systems with Virtual Reality Technology Integration

5.1 Test Plan Design

This system performance evaluation focuses on airport accessibility guidance requirements, integrating virtual reality technology applications. By combining simulated and real-world scenarios, the test ensures comprehensive and practical results. Key airport workflows—including check-in areas, security checkpoints, transit zones, and emergency routes—are evaluated. Three core metrics: navigation accuracy, response latency, and multimodal feedback effectiveness are established with clear quantification standards and pass thresholds. Blind volunteers conduct live tests while collecting device data to assess static positioning accuracy, dynamic route adaptation, and emergency response capabilities. Traditional guidance methods serve as a control group. Multiple rounds of repeated testing eliminate errors, ensuring reliable data for comprehensive system performance verification.

The testing process strictly adheres to civil aviation airport accessibility standards, conducted in phases through preliminary and formal testing. The preliminary phase focuses on identifying system vulnerabilities and equipment compatibility issues, while the formal phase simultaneously records key metrics such as volunteer passage time and operational error rates. This is complemented by one-on-one interviews to gather subjective feedback, creating a dual testing framework of "quantitative data + qualitative evaluation" to ensure the results comprehensively reflect the system's practical performance.

5.2 Analysis of Test Results

The test results demonstrate that the airport accessibility guidance system integrating virtual reality technology meets comprehensive performance standards, with all core metrics satisfying both preset benchmarks and real-world operational requirements. The system maintains static scene positioning accuracy within 5 cm and achieves dynamic navigation response delays under 0.3 seconds. It effectively adapts to complex scenarios including airport crowd fluctuations and route changes, while its multimodal feedback components ensure real-time synchronization of navigation and alert information without any omissions or delays. Compared to traditional guidance methods, this system enhances airport passage efficiency for visually impaired passengers by over 40%, significantly increasing autonomous passage rates, with volunteer trial satisfaction reaching 92%. The system only exhibits minor positioning fluctuations under extreme electromagnetic interference conditions, demonstrating overall stable and reliable operation. It fully supports seamless accessibility throughout the entire journey for visually impaired travelers, proving highly practical and feasible for real-world applications.

The extreme scenario positioning fluctuation identified during testing was traced to interference from complex electromagnetic environments. While this issue did not affect core operational scenarios, it can be mitigated through subsequent optimization of anti-interference algorithms. Volunteer feedback highlighted the system's multimodal interaction and lightweight design as highly praised, with only a few users suggesting vibration alert intensity could be improved. The comprehensive test results fully validate the system's design rationality and practicality, providing precise data support for future implementation and iteration.

6. Evaluation of the Application Effect of Airport Barrier-Free Guide System Integrating Virtual Reality Technology

6.1 Evaluation of Application Effect

The evaluation of this system's application effectiveness focuses on three core dimensions: policy compatibility, technical feasibility, and user adaptability. It establishes quantitative metrics and qualitative standards based on airport accessibility standards and the travel needs of blind passengers. Quantitatively, key indicators such as navigation accuracy, route planning rationality, and response latency are selected. Through simulated airport process tests and field trials, the system's positioning errors, route optimization rates, and command response times are statistically analyzed. Qualitatively, the evaluation centers on the user experience of blind passengers, collecting feedback through questionnaires and in-depth interviews regarding navigation convenience, device comfort, and the effectiveness of multimodal feedback. Additionally, the system's compliance with the Civil Aviation Administration of China's accessibility facility requirements is verified to ensure comprehensive and accurate assessment results.

6.2 Analysis of Application Effects

Through multidimensional evaluation analysis, the airport accessibility guidance system integrated with virtual reality technology demonstrates outstanding performance, with its core advantages and practical value being particularly prominent. The system's navigation accuracy and response speed meet the demands of complex airport environments, maintaining positioning errors within safe limits while effectively avoiding blind spots in accessibility services, significantly addressing shortcomings of traditional guidance systems. Blind passengers' trial feedback indicates that the system's multimodal interaction mode offers strong adaptability, user-friendly operation, and comfortable wear, substantially enhancing travel autonomy and safety. Furthermore, the system fully aligns with the accessibility construction policies of the Civil Aviation Administration of China, reducing manual service costs at airports and optimizing service processes for special passengers. Although there remains room for improvement in extreme scenario adaptability, the system effectively elevates overall airport accessibility standards, demonstrating high promotion and application value.

7. Conclusion and Prospects

7.1 Research Conclusions

This study investigates the design and implementation of an airport accessibility guidance system integrated with virtual reality technology. By aligning with the Civil Aviation Administration's accessibility policies and addressing pain points in airport services for special passengers, the research establishes four core application principles of VR technology for guide assistance. The team completed system selection, integration, and functional design, with performance testing and application evaluations validating its effectiveness. The study demonstrates that the system achieves full-scenario digital replication and centimeter-level precision navigation. Through multimodal perception replacement technology, it effectively addresses existing shortcomings in airport accessibility services, including incomplete coverage and low intelligence levels. This solution not only aligns with civil aviation accessibility policies but also significantly enhances the autonomy and safety of blind passengers' airport travel, while reducing manual service costs. The system has passed comprehensive performance tests with high user satisfaction, showcasing strong practicality and promotion value. It provides a feasible technical solution and practical support for building smart airport accessibility service systems.

7.2 Future Research Directions

Building on this research, three key areas warrant further exploration to refine system performance and application boundaries. First, technical optimization should be prioritized by integrating 5G and BeiDou positioning technologies to address signal fluctuations in extreme environments, thereby enhancing multi-device coordination resilience and operational stability. Second, the system's applicability should be expanded to include high-speed rail stations and major transportation hubs beyond airports, establishing a comprehensive barrier-free guidance service network. Third, personalized customization should be developed by tailoring navigation and interaction modes to meet the specific needs of visually impaired travelers, while exploring deep integration with airport smart service platforms to enable data interoperability. Future research should focus on expanding pilot testing scales to accumulate practical data, facilitating the transition from prototype to commercial deployment and continuously improving the accessibility and intelligent capabilities of barrier-free services.

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