ORIGINAL ARTICLE

Immersive Navigation in the Lü-dao Garden: Integrating AR, VR, and Virtual Agents

Cheng-Yu Wei[1], Hsin-Yi Wang[1], Han-Pang Huang[1,*], Yu-Lin Zhao[1], and Nai-Huei Hou[2]

[1]*Department of Mechanical Engineering, National Taiwan University, Taipei 106, Taiwan*

[2]*Department of Chinese Literature, National Taipei University, Taipei 106, Taiwan*

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Corresponding author: hanpang@ntu.edu.tw

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Abstract: This study presents a dual-modal AR/VR framework for the digital reconstruction and narrative navigation of the Lü-dao Garden (履道園), a lost Tang Dynasty heritage site associated with the poet Bai Juyi. While existing digital heritage approaches often emphasize geometric reconstruction and visual realism, they typically lack semantic interpretation and interactive narrative guidance. To address these limitations, the proposed system integrates remote VR immersion with on-site AR navigation based on a digital twin concept. A virtual agent is further introduced to provide semantic guidance, enabling the translation of spatial semantics derived from classical Chinese poetry into interactive AR/VR elements. This design transforms traditional cultural representation from passive observation into an active and exploratory learning experience. The results demonstrate that the proposed framework enhances user engagement and spatial understanding, while providing a scalable approach for semantic-driven digital heritage applications.

Keywords: Educational software, Virtual reality, Human centered design, Computer-aided design, Cultural schemas, Transdisciplinary.

Introduction

As large-scale models become increasingly common, there is a rising interest in Extended Reality (XR) technologies. This heightened attention is driven by the gradual dismantling of technical obstacles that once impeded widespread adoption. Therefore, particularly in the realms of entertainment and historical scene exploration, XR technology holds the potential to revolutionize these industries by delivering immersive experiences and innovative solutions, allowing learners to benefit from deeply engaging educational experiences. XR technologies encompass Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). This paper explores how AR and VR technologies provide an interactive virtual educational platform for learner, visitors and tour guides. It begins by examining the applications and advancements of AR and VR systems within the context of garden navigation.

In navigation applications [1-5], the seamless integration of reality and information is imperative for effective guidance. Consequently, AR or MR emerges as a more viable and intuitive solution. AR or MR applications are frequently employed to facilitate human cognition by bridging the gap between tangible reality and abstract concepts.

In the realm of cultural heritage, virtual reconstruction plays a pivotal role, as evidenced by the work presented in [6], which focuses on the digitization and VR application of the Roman Augustus Forum. This endeavor represents a collaborative effort among interdisciplinary experts, who meticulously reconstructed historical building models using extensive historical documentation and data collected on-site. Similarly, VR technology has been employed to reconstruct Qi Biaojia's Writing of Yushan garden construction process and landscape design, aiming to uphold Chinese classical garden culture and ideals [7]. Despite the comprehensive reconstruction efforts, it is notable that there is a lack of audio or text guides about the two researches to accompany the virtual experience. A study [8] on mixed reality in the context of cultural heritage enables

students to visualize high-resolution 3D scans of ancient statues. However, it provides limited supplementary information regarding the historical context of these artifacts. Literature [9] and [10] highlight the positive impact of VR in the fields of engineering and cultural education, respectively. Moreover, emerging applications of VR technologies represent a promising direction for enhancing student engagement by facilitating increased attentional focus and intrinsic motivation within educational contexts [11].

As for robotic and mechanical applications, the integration of AR navigation [12-14] serves to provide users with an immersive operational milieu. This immersive environment facilitates user decision-making processes, particularly in the context of robot programming. Concurrently, these endeavors prioritize the refinement of tracking precision and enhancement of user experience throughout the navigation process.

The primary objective of this study is to bridge the temporal and cultural gap between ancient Chinese literati lifestyles and modern audiences through a dual-modal AR/VR framework. By integrating pedagogical goals with immersive entertainment, the system aims to transform the passive consumption of classical culture into an active, exploratory experience. Beyond simple navigation, this research seeks to visualize the spatial semantics and philosophical underpinnings of traditional gardens, thereby fostering a deeper resonance with classical aesthetics among contemporary learners.

To ensure ubiquitous access and high immersion, the proposed navigation system is structured into Remote and Local modules. Adopting a Digital Twin concept, this framework offers parallel experiences for co-located and remote users. This dual-modal architecture ensures that the cultural heritage is accessible both physically (via AR) and virtually (via VR), transcending geographical limitations. For museums or heritage sites currently utilizing static QR code systems, this framework represents a significant evolution toward dynamic, multi-sensory storytelling.

The primary objective of this study is to bridge the temporal and cultural gap between ancient Chinese literati lifestyles and modern audiences through an AR/VR-based framework. By integrating pedagogical goals with immersive entertainment, the system aims to transform the passive consumption of classical culture into an active, exploratory experience. Beyond simple navigation, this research seeks to visualize the spatial semantics and philosophical underpinnings of traditional gardens, thereby fostering a deeper resonance with classical aesthetics among contemporary learners.

Among the vast array of Chinese tourist destinations, classical gardens serve as vital repositories of ancient lifestyles and philosophies. However, comprehending these spaces solely through textual information or verbal explanations can be challenging. AR presentations, featuring superimposed models and animations, offer users a dynamic demonstration of Chinese culture, while VR technology enables immersive exploration when physical visits are impractical or sites have degraded. Ultimately, this work aims to synergistically blend modern technology with the rich cultural context of traditional Chinese gardens.

Given that the material heritage of the Tang and Song dynasties is largely scarce—with most extant gardens dating only to the Ming and Qing periods—this study focuses on the digital reconstruction of the Lü-Dao Garden, the historic residence of the poet Bai Juyi. By analyzing poetic descriptions and historical records, the proposed system translates abstract literary content into navigable spatial representations, allowing users to experience the relationship between cultural expression and physical environment.

In recent years, VR and AR technologies have been widely applied in digital heritage reconstruction, with approaches ranging from photogrammetry-based modeling to immersive virtual environments. While these methods significantly improve visual realism and accessibility, most existing systems primarily emphasize geometric reconstruction and visual presentation, often lacking mechanisms for semantic interpretation and interactive narrative guidance. In addition, many AR/VR navigation systems are designed as single-modal solutions, either focusing on remote VR exploration or on-site AR enhancement, resulting in limited continuity between different usage scenarios.

To address these limitations, this study proposes a dual-modal AR/VR framework based on the digital twin concept, integrating remote VR immersion with local AR navigation. A virtual agent is further introduced as a semantic mediator, enabling the transformation of spatial semantics derived from classical Chinese poetry into interactive AR/VR elements. This design shifts digital heritage systems from static visualization toward dynamic, experience-driven cultural learning.

From a system implementation perspective, multiple platforms have been adopted in digital twin and immersive robotics applications, including Gazebo, NVIDIA Isaac Sim, and Unity. These platforms differ in their design focus: Gazebo is commonly used for physics-based simulation and ROS-integrated control validation, Isaac Sim emphasizes high-fidelity sensor modeling and AI-driven perception tasks, while Unity provides strong support for real-time rendering, user interaction, and AR/VR application development.

In this work, Unity is selected as the primary

development platform due to its flexibility in constructing interactive environments and its suitability for integrating AR/VR functionalities with user-centered experience design. To ensure ubiquitous access and high immersion, the proposed navigation system is structured into Remote and Local modules. This architecture enables parallel experiences for both co-located and remote users, allowing cultural heritage content to be accessed physically through AR and virtually through VR.

This work is an extension of our preliminary study presented at Automation 2025 [15], incorporating a refined architecture and expanded user experience evaluations.

Reconstruction

The proposed AR navigation framework for the digital revival of the classical garden is illustrated in the flowchart in Figure 1. The methodology begins with a comprehensive synthesis of historical archives, where reconstructed elements are rigorously cross-referenced with period-specific materials to ensure structural and historical authenticity. Following this, a feasibility-significance filter is applied: sites are strategically selected based on their technical reconstructability and their narrative importance to the overall user experience. This dual-layer preparation ensures that the final AR navigation is both historically grounded and technically optimized.

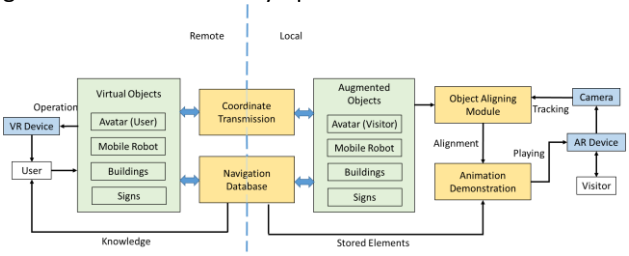


Figure 1. Reconstruction Process of Lü-dao Garden.

Subsequently, we initiate the process of modeling the 3D CAD model based on the finalized planar configurations. To facilitate building modeling, we employ CAD software called SketchUp, commonly utilized for interior and landscape design purposes. The foundational terrain is constructed by outlining its contours and subsequently elevating the land accordingly. Following the delineation of ground trails, CAD models of buildings and bridges are meticulously crafted, with their components adjusted to appropriate sizes by pertinent literature. These structures must not only be conducive to habitation but also seamlessly integrate with the surrounding environment while preserving their original functions. For instance, as illustrated in Figure 2, the arch bridge must possess sufficient height to accommodate the passage of boats beneath it.

Figure 2. Lü-dao Garden in SketchUp.

In this research, we reconstruct the classical garden known as Lü-dao Garden, immortalized by the renowned Chinese poet of the Tang Dynasty, Bai Juyi. Lü-dao Garden, situated in the ancient Chinese city of Luoyang, specifically in its southeastern region, was lauded by Bai Juyi as the most picturesque corner of Luoyang. Bai wrote a wealth of garden poems and a prose which depict the layout and the entire viw of the garden, as well as showing the diverse daily and cultural events there clearly bring alive his life and close interaction with the garden. Notably, Bai Juyi holds the distinction of being the first literati figure in Chinese history to extensively expound upon gardening concepts within his literary works. He took great pleasure in the intricate layout of his beloved garden and meticulously documented various minor impromptu renovations throughout his lifetime. Given that Lü-dao Garden boasted the most comprehensive textual records among Tang Dynasty gardens, faithful recreation became imperative.

Subsequently, we delve into the design and configuration of the landscape elements and the planning of the dynamic lines of the scenery. First, according to the literature, Lü-dao Garden was about 80-90 meters wide and 100-110 meters long. There was a river called Yishui (伊水) flowing by Lü-dao Garden. Bai Juyi considered water a critical element of a classic garden design. Therefore, he gathered some of the river water into a pond. In Pond Previous (池上篇序) by Bai Juyi, the area of the pond is said to be about 2000 square meters. Insights from Ren Jian's Ludaoli of Tang Dynasty, Bai Juyi's Garden in Luoyang (任見〈唐代履道里，洛陽白氏園〉), suggest that Bai Juyi's primary living quarters were positioned in the northeast sector of the garden, as water was sourced from the west side of Lü-dao Garden. The focal point of the garden lies in its southern portion, where a central pool is encircled by numerous edifices, three small islands, and bridges amidst an assortment of plant life and bamboo groves — constituting prominent

features following the pond. These islands, christened South Island, North Island, and Middle Island by posterity, boast distinct characteristics. North Island is adorned with abundant cherry blossoms along its trails, while Middle Island features moss-covered surfaces and scattered lotuses within the pond, imbuing the scene with an air of mystique.

The water in the stream flows from under the northwestern wall, spreads into the stream bank, and narrows the width of its course before pouring into the south pond. A side stream is excavated in the middle and diverted eastbound into the Residential Zone. The water is then obstructed by objects like bamboo fences adjacent to the residential zone to create a sight of blustering cascading stream water for some added effect of wilderness. The Stream water that goes into the residence forms a little pond near the kitchen, not for visual pleasure, but for everyday use.

Following the arrangement of the 2D map depicted in Figure 3, the subsequent phase involves translating the planar design into a 3D model. Initially, SketchUp is employed to delineate the terrain's topography and the spatial distribution of buildings. Additionally, the paths and pond are meticulously crafted, as shown in Figure 4.

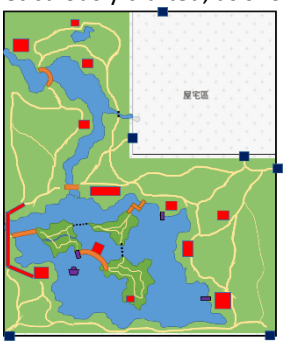


Figure 3. 2D Planar Map of Lü-dao Garden.

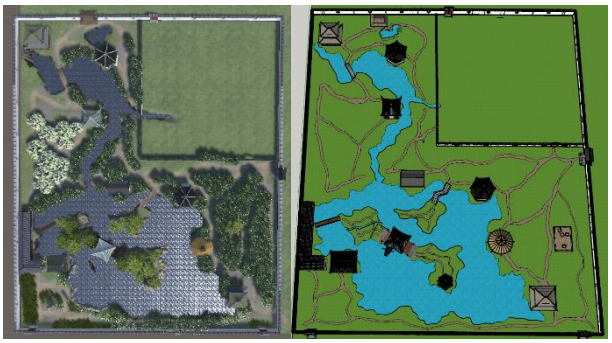


Figure 4. 3D Model in Unity and SketchUp.

Upon completing the base models, assets were exported to Unity for environmental rendering and interaction design. The implementation steps are detailed below:

- Terrain and Topography: Drawing from the 2D map, the ground plane was extruded within SketchUp. To address the rigidity of CAD geometry, angles were smoothed in Unity to achieve an organic terrain appearance. Textures and volumetric grass were subsequently applied to enhance realism (Figure 5).
- Architectural Structures: Buildings, bridges, and pavilions were modeled based on literature constraints and exported as FBX files. Figure 6 depicts the finalized arbor on the island.
- Vegetation and Rockery: Plants and rocks are essential for establishing the "mysterious" atmospheric quality of Chinese gardens. To manage the computational load of high-density vegetation, a tree-generation module was utilized in Unity to optimize mesh visualization. Figure 7 illustrates the rock formations surrounding the pond.
- Interactive Artifacts: To transcend static observation, the system incorporates dynamic elements. Movable objects, such as boats (Figure 8) and wine cups, are simulated to replicate the lifestyle of ancient literati. These interactive assets allow users to engage with the environment, fostering a sense of presence akin to that of a Tang Dynasty scholar.

Figure 5. Ground of Lü-dao Garden.

Figure 6. Arbor on the Middle Island.

Figure 7. Rock of the Lü-dao Garden.

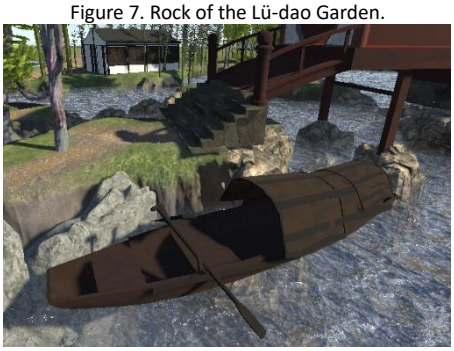


Figure 8. Boat at the South Pool.

Implementation

In navigation, the accurate positioning of tourists within the garden holds paramount importance. Consequently, the map displaying the tourist's current location is prominently featured in the corner of the AR device. The arrangement of the user interface (UI) elements within the AR device is delineated in Figure 9. Beneath the map and introductory text, buttons facilitating connectivity to remote sites are situated, providing users with seamless access to additional resources.

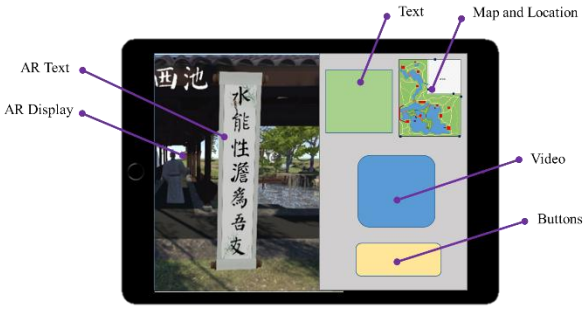


Figure 9. Navigation UI in AR device.

Chinese couplets hold a special significance in literature and decoration. While the practice of displaying couplets on pillars and doors was not common during the Tang Dynasty, the visualization of couplets through AR technology can enrich visitors' experiences and immerse them in the atmosphere and lifestyle of the garden. By presenting couplets written by Bai Juyi, visitors can perceive scenes that correspond to the poetic descriptions, thereby enhancing their appreciation of the garden's aesthetic and evoking literary sentiments, as depicted in Figure 10.

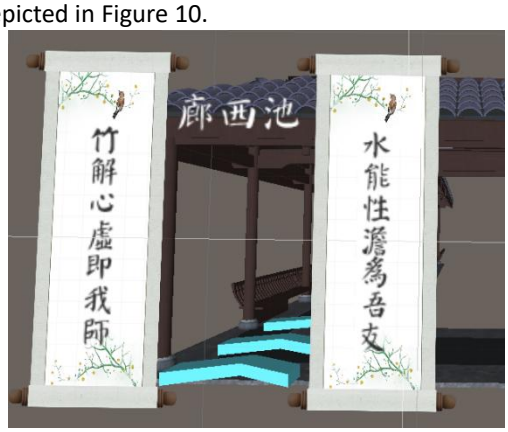


Figure 10. Couplet Visualization in Unity.

As tourists move from one site to another within the garden, it is essential for them to have clear directional guidance. To facilitate this, virtual arrows are strategically positioned along the path when tourists utilize the AR device. Once the marker on the sign is tracked, the direction to the next pre-arranged site is displayed. This directional visualization of the path is shown in Figure 11.

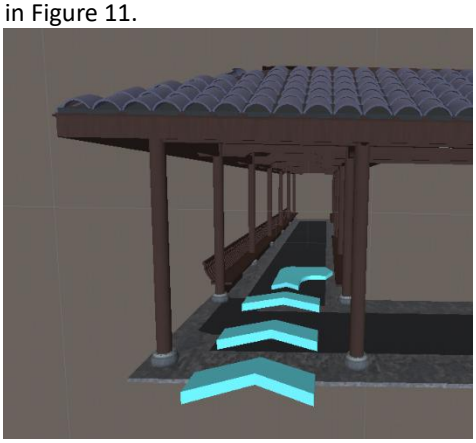


Figure 11. Path Visualization in Unity.

Due to considerations such as quarantine measures, distance factors, and relic preservation, remote navigation emerges as a safer and more efficient option for visiting cultural sites. However, to facilitate remote navigation effectively, the implementation of a suitable method for moving within the virtual scene is imperative. Among these methods, teleportation stands out as a crucial function. This feature enables users to instantly transport to a designated spot without physically traversing the scene. The practical application of teleportation is demonstrated in Figure 12. Notably, teleportation offers a distinct advantage over gradual

view changes by mitigating sensations of dizziness and disregarding spatial constraints, thereby enhancing user comfort and experience.

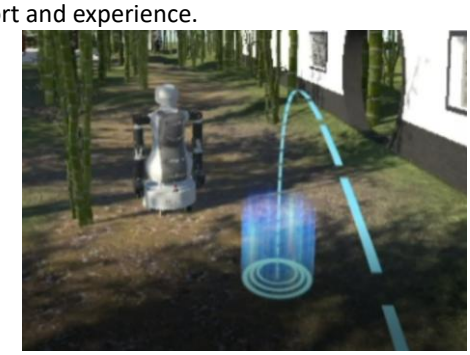


Figure 12. Teleporting Pointer in VR Scene.

To guide visitors, a virtual agent named Mobi is designed within the Unity environment. Mobi serves as an interactive interface bridging the user and the historical context (Figure 13). By humanoid configuration, Mobi can represent the tour guide in the Lü-dao Garden instead of the real one. The guidance of Mobi provides clear knowledge of the visiting order.

Figure 13. The robot Mobi (developed by our lab) Model in Unity.

Upon importing the building models and garden decorations into the VR scene, animations are incorporated into the garden's introduction. These animations are crafted based on the narrative of Lü-dao Garden, aiming to showcase the lifestyle of Bai Juyi. To illustrate Bai Juyi's daily activities, an ancient model is introduced into the scene, as depicted in Figure 14. Throughout the garden navigation experience, this model can perform various movements such as walking, observing, or savoring wine — activities that Bai Juyi commonly enjoyed in his garden. Importantly, these movements are synchronized with specific scenes within the garden, allowing users to immerse themselves in and appreciate the entirety of the navigation process.

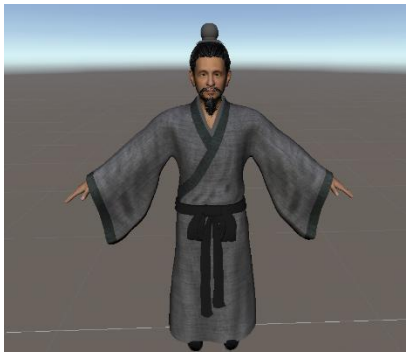


Figure 14. Human Model in Unity.

As visitors enter the garden, a virtual robot guides them toward the next site, leading them to a curtained area where they can immerse themselves in the ambiance of Bai Juyi's era. During this period, gardens served not only as spaces for relaxation and contemplation but also as focal points of landscape and daily life activities. By presenting a virtual representation of Bai Juyi, visitors can gain insights into the daily routines of literati within the garden. The reconstruction of Lü-dao Garden not only offers visualizations of landscapes but also provides a platform for experiencing the lifestyle of literati through 3D visualization, offering a multifaceted perspective beyond textual information.

Experiments and Implementation

Given the practical challenges of deploying a full-scale test in the reconstructed heritage site (which no longer exists physically), this study establishes a scaled-down indoor simulation to validate the system's narrative logic and interaction stability. The indoor environment mimics the garden's spatial layout using a reduced coordinate system. Figure 15 illustrates the simulation scenario of navigating the garden within a room. Blue circles represent mobile robots, while black circles depict tourists. The mobile robot guides tourists from site 1 to site 2, allowing them to perceive the robot as Bai Juyi strolling through his garden. Several assumptions underpin this navigation demonstration. Firstly, the garden's map and configuration are reconstructed and known for path arrangement. Secondly, markers corresponding to each site and their locations within the garden are pre-set to allow the AR device to capture the tourist's position accurately. Thirdly, the garden's terrain is sufficiently flat to facilitate the movement of the mobile platform. The virtual guide system utilizes pathfinding algorithms (e.g., NavMesh in Unity) to navigate the virtual terrain, ensuring the avatar moves naturally along the garden paths without passing through static objects.

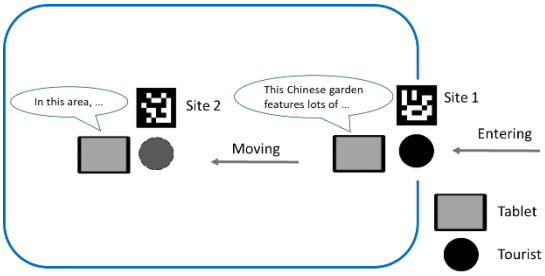


Figure 15. Scenario of Navigation Demonstration.

In the navigation case, the coordinate definition and relationship are shown in Figure 16. Similar to multi-user virtual environments, the coordinate system aligns the remote user's VR perspective with the digital reconstruction. The coordinate relationship is defined by the tracking function of the VR headset. When the remote user moves, the coordinate is calculated. The user can see the virtual building as if it is located in front of the screen. Different from the maintenance scenario, there are fixed markers set on the real billboard in the garden. The marker is set to recognize the position of the tourist in the garden. From the perspective of the tourist, the coordinate relationship $M_R^C T$ plays a pivotal role in enhancing AR visualization and interaction. By accurately mapping the tourist's position within the garden, AR technology can overlay virtual elements onto the real-world environment, providing contextual information and guiding the tourist along designated paths.

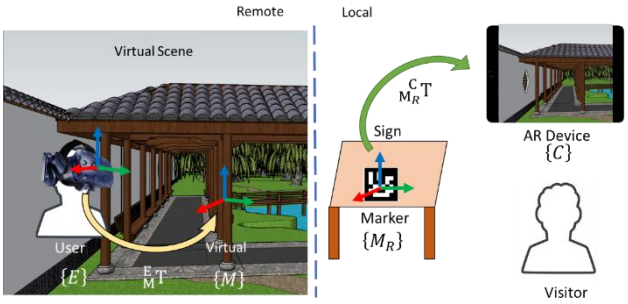


Figure 16. Coordinate Relationship in Navigation.

In Lü-dao Garden, numerous sites await exploration, each offering unique experiences for visitors. To accommodate the limitations of physical space and prevent exceeding room dimensions, the teleporting function is implemented in remote navigation. As depicted in Figure 17, the remote guide can traverse the expansive virtual landscape of Lü-dao Garden within the VR environment. Although navigating the entirety of Lü-dao Garden on foot using indoor devices may be impractical due to its size, the teleport function enables swift and efficient exploration of the virtual garden. Upon entering specific sites, visitors encounter informative texts and couplets, providing guidance and enhancing the navigation experience.

Figure 17. VR Teleporting Scene of the Lü-dao Garden.

When the user enters the gate for the Lü-dao Garden, the Bai Juyi's motivation of building this garden is introduced by the texts like Figure 18. At the same time, these texts are repeated by the computer voice. The visitor can hear or read the guiding words.

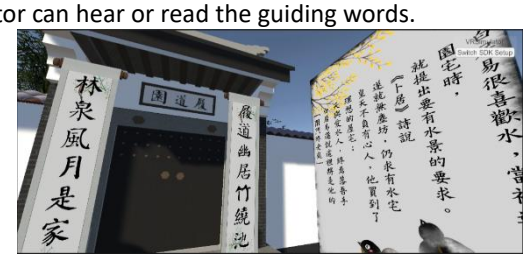
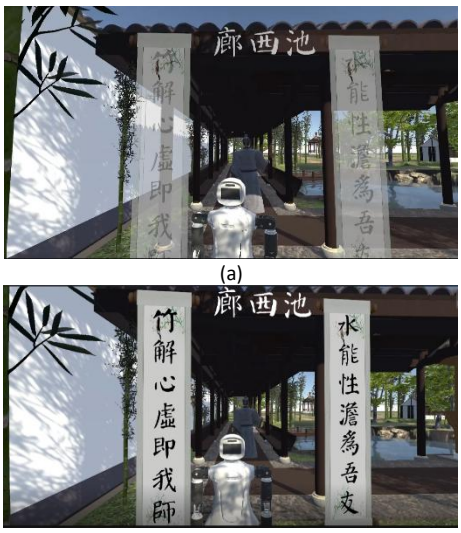


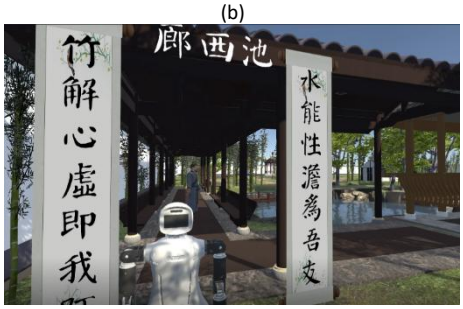
Figure 18. Navigation Scene of the Gate in VR.

In Figure 19, the navigation of the west aisle is illustrated within the VR scene. Upon entering a designated area within a specific site, both the couplet and a humanoid model become visible, as depicted in Figure 19 (a). As the user progresses along the aisle, the virtual representation of Bai Juyi begins to walk forward, as shown in Figure 19 (b). Subsequently, after reaching the intended destination, the humanoid model turns towards the pond and gazes eastward, as depicted in Figure 19 (c). The west aisle is renowned for moon watching, and this animation aims to provide users with an understanding of the historical context and activities that once occurred in this area.



(a)

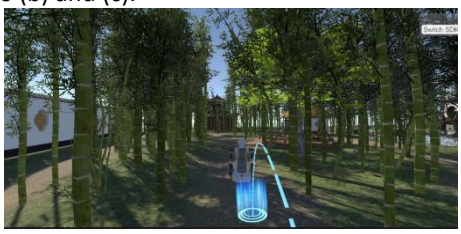
(b)



(c)

Figure 19. Navigation of the West Aisle. The subfigures (a) to (c) are arranged in chronological order.

At the food storage area located near the east pond, a visualized introduction is presented, as depicted in Figure 20 (b). To ensure clear and structured guidance, a humanoid robot model named Mobi is integrated into the VR environment. Mobi is capable of walking within the garden and halting at designated areas to lead visitors, akin to the scenario depicted in Figure 20 (a). Upon the visitor's arrival at the designated area through teleportation, the couplet becomes visible, and the humanoid model initiates its movements, as illustrated in Figure 20 (b) and (c).



(a) Teleporting View and Mobi Leading

(b) Introduction Visualization

(c) Couplet and Human Model

Figure 20. Navigation of the Food Storage.

To offer a captivating view of the pond within Lü-dao Garden, an animation depicting the sailing of a boat is incorporated into the navigation experience. As depicted in Figure 21, a boat is positioned near the island, allowing visitors to immerse themselves in the serene ambiance of the pond while aboard. To enhance the navigation experience, Bai Juyi is also included on the boat, providing visitors with companionship and guidance throughout their journey.

Figure 21. Sail with Virtual Bai Juyi.

Additionally, at the arbor within Lü-dao Garden, visitors have the opportunity to relax and unwind by sitting on chairs and enjoying tea within the VR environment. In Figure 22, Bai Juyi is depicted alongside the visitor, partaking in the tranquil atmosphere while indulging in tea. This immersive experience allows visitors to fully appreciate the beauty and serenity of Lü-dao Garden while enjoying the company of Bai Juyi.

Figure 22. Drink Tea with Virtual Bai Juyi.

In local navigation, the visualized couplet is displayed as depicted in Figure 23. To ensure optimal visibility and readability, the words are presented floating in the air rather than being attached to pillars. The couplet in Figure 23 praises the virtues of water and bamboo. In Chinese culture, literati often use these elements to symbolize their ideal characteristics and personal aspirations.

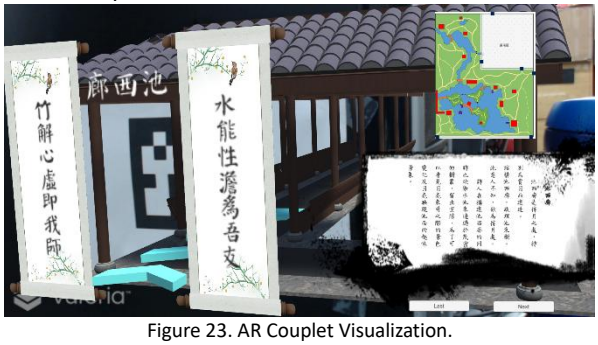


Figure 23. AR Couplet Visualization.

After the visitor follows the arrow to the next

marker, they can utilize an AR device to visualize the image of the moon, as shown in Figure 24. This allows visitors to enjoy the simulated scenery while exploring the garden, enhancing their overall experience.

Figure 24. Simulated Moon in AR.

Conclusion

This study presents the digital reconstruction of the Lü-dao Garden and proposes a dual-modal AR/VR framework for immersive cultural heritage navigation. By integrating remote VR exploration with on-site AR enhancement, the system enables a continuous user experience that overcomes the limitations of single-modal navigation approaches.

Unlike conventional digital heritage methods that primarily focus on geometric reconstruction and visual presentation, this work introduces a virtual agent to provide semantic guidance within the environment. Through this mechanism, users are able to actively engage with cultural narratives rather than passively observe reconstructed scenes. Furthermore, the study demonstrates a novel approach to translating spatial semantics derived from classical Chinese poetry into interactive AR/VR elements, transforming static cultural content into dynamic and experiential learning processes.

Therefore, this research extends digital heritage reconstruction from a geometry-centered paradigm toward a semantic-driven and interaction-oriented framework, highlighting the importance of user experience and cultural interpretation in digital twin applications. This directly addresses key limitations identified in existing systems, including the lack of semantic interpretation, limited user interaction, and discontinuity between AR and VR experiences.

Nevertheless, several limitations remain. The visual realism of the Lü-dao Garden can be further improved, and future work will explore more efficient rendering strategies to support large-scale environments.

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