

Castillo de San Marcos AR: Spatial Augmented Reality Interactive Learning System for Cultural Heritage Education

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Abstract—This paper presents a spatial Augmented Reality (AR) interactive learning system designed to enhance cultural heritage education and immersive human-computer interaction using Castillo de San Marcos in St. Augustine, Florida. The system employs Vuforia Ground Plane spatial tracking to anchor reconstructed historical content directly onto the physical environment of the fort, enabling situated and contextual learning experiences. Users explore architectural structures, defensive layouts, and historical narratives through interactive spatial visualization and AR-based storytelling. The proposed system contributes to research in interactive educational technologies and spatial computing by integrating markerless AR interaction with cultural heritage interpretation in outdoor environments. Preliminary observations indicate improved user engagement, spatial comprehension, and experiential learning potential. Future work includes formal user evaluation, collaborative learning features, and expanded historical reconstruction.

Keywords—*augmented reality; cultural heritage; immersive learning; interactive education; spatial AR.*

I. INTRODUCTION

Cultural heritage sites provide opportunities for experiential and contextual learning. Traditional interpretation methods often rely on static signage and narration, which may limit user engagement and spatial understanding. Augmented Reality (AR), originally defined by Azuma [1] as the integration of virtual and physical environments in real time, enables digital content to be embedded within real-world environments to support situated learning. Billingham et al. [2] further demonstrated the growing role of AR in Human-Computer Interaction (HCI) and interactive visualization. Castillo de San Marcos presents a historically significant masonry fort whose architectural and defensive structures benefit from spatial visualization. This work presents a spatial AR system that overlays reconstructed historical elements onto the physical site to enhance immersive learning, interactive exploration, and contextual engagement.

Augmented Reality has emerged as an effective medium for cultural heritage education by enabling immersive and situated learning experiences. Unlike traditional interpretation methods, AR allows digital historical reconstructions and contextual information to be directly

integrated with the physical environment, improving spatial understanding and learner engagement. Prior research has shown that AR enhances conceptual comprehension, supports experiential learning, and increases motivation by transforming passive observation into interactive exploration [3][4]. These capabilities make AR particularly suitable for historical sites where spatial context and environmental immersion are essential for meaningful learning.

This work is relevant to the conference themes of advanced Human-Computer Interaction, immersive educational technologies, contextual interaction, and interactive digital heritage systems. By combining spatial Augmented Reality, situated learning, and interactive visualization, the proposed system demonstrates how immersive interfaces can enhance user engagement and experiential learning within real-world cultural heritage environments.

The rest of the paper is structured as follows. Section II reviews related work in Augmented Reality and cultural heritage education. Section III presents the system design and implementation of the spatial AR learning platform. Finally, Section IV concludes the paper and discusses future work.

II. RELATED WORK

Augmented Reality has been widely applied in cultural heritage education to enhance engagement and contextual understanding. AR enables digital reconstructions to be overlaid onto physical environments, supporting experiential learning and improved knowledge retention. Fonseca et al. [5] explored mixed reality applications for cultural heritage visualization and interactive learning environments. Jantke et al. [6] demonstrated an AR system for Castle Scharfenstein integrating gamification and visitor interaction to enhance exploration and engagement. Situated learning theory emphasizes learning within real-world contexts, which AR effectively supports. While many AR heritage systems rely on markers or indoor deployment, fewer studies explore spatial AR in indoor and outdoor environments. Situated learning theory emphasizes learning within real-world context, which AR effectively supports. While many AR heritage systems rely on markers or indoor deployment, fewer studies explore spatial AR in indoor/outdoor environments.

Numerous studies have demonstrated the educational benefits of Augmented Reality in cultural heritage contexts. AR has been shown to improve knowledge retention and engagement by enabling users to interact with reconstructed historical environments and contextual visualizations [3]. Furthermore, AR-based heritage systems promote experiential and inquiry-based learning, allowing visitors to actively explore historical narratives rather than passively consume information [4]. These findings highlight the potential of AR as an effective tool for enhancing cultural heritage interpretation and educational outcomes.

Situated learning theory suggests that learning is more effective when knowledge is acquired within real-world contexts. AR supports this approach by embedding digital information directly within the physical environment. While many existing systems focus on indoor museum environments or marker-based AR, fewer works explore outdoor heritage interpretation using spatial ground-plane tracking. This work contributes by applying an AR to a masonry fort environment with spatially contextualized interaction.

III. SYSTEM DESIGN & IMPLEMENTATION

The system was developed in Unity using Vuforia Ground Plane technology. Ground Plane enables the detection of horizontal surfaces and allows digital models to be anchored without predefined visual markers. Reconstructed 3D architectural elements are overlaid onto the physical site to support spatial visualization and contextual learning. Figure 1 shows the 3D reconstruction model of Castillo de San Marcos.

The application was implemented in Unity and deployed on a mobile handheld platform using Vuforia Ground Plane tracking for markerless spatial anchoring. Reconstructed 3D models were optimized for mobile rendering performance to support stable real-time interaction in outdoor environments. Users interact with the virtual content through touchscreen-based translation, rotation, and scaling controls integrated within the Graphical User Interface (GUI).



Figure 1. 3D Model of Castillo de San Marcos.

Spatial AR does not rely on predefined image targets or fiducial markers to align virtual content with the real environment. Instead, it detects characteristic features and planar surfaces of a scene in real time, enabling flexible deployment in unprepared environments and supporting natural user interaction. This approach reduces setup complexity and allows AR content to be anchored directly

onto real-world terrain, which is particularly suitable for outdoor cultural heritage environments such as Castillo de San Marcos. Advances in computer vision and mobile sensing technologies further enable spatial systems to utilize the physical environment itself as a tracking reference, improving usability and immersion [7].



Figure 2. 3D Reconstruction of Castillo de San Marcos in a Spatial AR application.

As shown in Figure 2, users initialize the system by scanning the environment to detect a ground plane for spatial anchoring. Once the anchor is established, AR overlays are aligned with the physical structure of the fort. Contextual hotspots provide access to historical narratives, reconstructed visualizations, and explanatory content. On-site deployment demonstrates the feasibility and robustness of spatial AR under varying indoor/outdoor lighting conditions. The application further enables users to manipulate the reconstructed castle model through rotation and scaling interactions via the graphical user interface (GUI) on the mobile device screen.

IV. CONCLUSION AND FUTURE WORKS

Spatial AR enhances spatial comprehension and engagement in outdoor heritage environments, although challenges remain in tracking stability, lighting variability, and reconstruction accuracy. Optimization for mobile performance is essential to ensure a consistent user experience. Augmented Reality also offers clear pedagogical benefits for cultural heritage education by embedding contextual information directly within the physical

environment, thereby supporting situated learning and improving spatial cognition. Interactive visualization and user-driven exploration promote deeper understanding and engagement compared to traditional static interpretation methods, consistent with prior findings on AR's positive impact on learner motivation and comprehension [3][4].

Several limitations remain in the current implementation. Outdoor spatial tracking performance may vary under inconsistent lighting conditions and complex environmental surfaces. Mobile hardware constraints can also affect rendering performance and tracking stability in large-scale outdoor environments. In addition, the current system currently focuses primarily on single-user interaction and has not yet undergone formal user evaluation for learning effectiveness and usability assessment.

This paper presented a Spatial AR system for cultural heritage education at Castillo de San Marcos. The platform demonstrates the effectiveness of spatially anchored visualization for immersive historical learning. Future work will focus on controlled user evaluation, multi-user collaboration, and expansion of historical reconstruction and educational content.

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