A Review of Locomotion Techniques for Exploring Heritage Sites in Virtual Reality

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***Abstract*—This paper systematically reviews locomotion techniques in Virtual Reality (VR) for exploring heritage sites, focusing on methods that enhance user immersion and connection to virtual environments. Through a systematic literature review, this study categorizes the most commonly used locomotion methods, analyzes the rationale behind their selection and user experiences. The study finds that controller-based methods are most commonly used due to their familiarity. However, recent advancements in walking-based techniques like Walking in Place (WiP) and Redirected Walking (RDW) show greater potential for providing a more immersive experience. Despite technological challenges, these unmediated approaches could significantly enhance user presence of virtual heritage site exploration. The paper emphasizes the need for further research into integrating these advanced techniques in VR applications.**

Keywords—heritage site, place identity, virtual reality, locomotion.

I. Introduction

Physical walking around heritage sites is vital for reinforcing place identity, as it provides an immersive connection to the historical and cultural essence of a location. Research highlights how walking from origin to destination helps evaluate and preserve the unique heritage of areas through their physical components, such as building forms and pedestrian pathways [1]. The physical act of walking around a heritage site is crucial for building place identity as it allows individuals to directly engage with the historical and cultural significance of the location [2]. The simple act of walking is indispensable for maintaining and enhancing place identity, as it fosters a deep, personal connection to the historical and cultural fabric of a place.

Virtual Reality (VR) has become prevalent in virtual heritage (VH), offering access to 3D models of heritage sites and enabling immersive, interactive experiences that enhance both education and recreation. VR allows users to explore reconstructed historical environments from a first-person perspective, helping to shape a sense of place through virtual engagement with tangible elements [3].

Despite the benefits of VR for presenting heritage sites and its potential to enhance place identity, challenges remain, particularly in locomotion. Locomotion refers to the methods that allow users to move and orient themselves within a virtual environment (VE) [4]. Studies suggest that VR locomotion mimicking bipedal walking is more effective for exploring VEs [5], as it closely replicates natural physical space, enhancing presence and fostering a positive attitude toward the environment [6]. However, earlier attempts to implement this in VH have been limited by technological constraints and the need for physical space equivalent to the VE, which is often impractical for heritage sites.

Recent advances in walking-based VR locomotion offer promising solutions for heritage site exploration. Techniques include Walking in Place (WiP), which converts stationary walking into VR motion via sensors [7], omnidirectional treadmills [8]; Redirected Walking (RDW), which subtly alters the user's path to extend walkable areas without their awareness [9]; and procedural manipulation of VEs in real time through methods like Impossible Spaces (IS), where subspaces overlap without interacting (e.g., portals) [10] or Dynamic Layout Generation (DLG), which procedurally generates architectural elements in the VE to create a seamless path for the user within a limited physical space [11].

This article reviews research on VR in heritage site presentation, focusing on (1) the most common locomotion techniques, (2) the rationale for their use, and (3) user experiences with these techniques. The goal is to provide an overview of current research in virtual heritage, particularly regarding its application for supporting heritage site place identity in VR.

II. Literature Review

A. Sense of Place & Place Identity

Sense of place refers to the emotional and psychological attachment people form with a place through their experiences and cultural contexts [12]. It plays a critical role in the effectiveness of cultural heritage management, fostering collaboration between governments and local communities to support tourism and conservation policies [13].

Place identity is the cognitive aspects of sense of place, defines an individual's identity in relation to a specific location. It is shaped by a complex interaction of cognitive processes, emotional states, beliefs, goals, and behaviors, all influenced by the surrounding physical environment [14].

The significance of heritage sites in establishing place identity can be understood through three principles: 1) distinctness, which refers to the unique features of both tangible and intangible aspects; 2) continuity, which emphasizes the role of past memories and experiences; and 3) familiarity, which involves the combined impact of physical features and repeated events [15]. Distinctness is primarily related to the physical characteristics of the heritage site, continuity acknowledges the influence of time and recollection, while familiarity is shaped by the interplay of physical features and recurring events.

B. *Immersion and Presence in VR*

Experiencing tangible elements of place in VR requires both spatial presence and plausibility. Presence refers to the psychological sense of "being there" within the VR environment [16]. The quality of presence depends on the level of immersion provided by the VR system, which is defined as "the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses" [16]. Immersion in VR requires "matching," which refers to the synchronization between a user's body movements and sensory modalities, such as visual and vestibular feedback (e.g., as the head turns, the display changes accordingly) [16]. Immersion also necessitates self-representation, where the user perceives an embodiment within the virtual environment (VE). This embodiment enhances the user's sense of physical presence by reinforcing the alignment of body movements with visual feedback.

C. *Locomotion Techniques in VR*

Boletsis proposes VR locomotion typology that can be categorized into four aspects: interaction type, VR motion type, VR interaction space, and VR locomotion type [17]. There are 4-known category from the aspect of locomotion type: (1) Controller-based (C), this method uses a handheld controller with a joystick or touchpad. Moving the joystick or swiping the touchpad in a specific direction continuously moves the user within the virtual environment [18]; (2) Teleport (T), this method utilizes controller in a different manner. The user points the controller towards a desired location by activating the controller's button to instantly jumps to the selected location [18]; (3) Walk in place (WiP), a semi-mediated method where the user mimics walking by lifting their legs in place. Sensors in VR controllers or external tracking systems detect the walking motion and translate it into movement within the virtual environment [18]; (4) Redirected walking (RDW), a non-mediated method that enable user to walk in a natural way within a confined space by subtle manipulation of the virtual environment to create the illusion of a larger space. As the user walks in the physical world, slight adjustments are made to the virtual world's geometry, allowing for longer walks within a limited physical space without the user noticing [19].

III. Methodology

This study adopts a systematic literature review approach, defined by Cook et al. (1997) as an integrative article in which authors search for, select, and synthesize evidence on specific scientific questions, either qualitatively or quantitatively [20]. The research examines selected articles to gather information on the use of VR locomotion through the following research questions (RQs):

RQ1: What locomotion techniques are most commonly used in VR heritage site projects?

RQ2. What is the rationale behind their selection?

RQ3. What is the user experience with these locomotion techniques?

A. *Article Search & Appraisal*

The selection process of articles for review follows the PRISMA framework, a standardized method for ensuring transparency and reliability [21]. The process comprises three stages: identification, screening, and inclusion of articles.

In the first stage, a comprehensive search was conducted using keywords relevant to the research questions (i.e., "heritage site", "virtual reality", and "locomotion") in research databases, including Google Scholar, ScienceDirect, and SpringerLink. The second stage involved filtering results to include journal and conference articles published within the last three years (2021–2024). Subsequently, a critical appraisal was conducted, selecting articles based on the relevance of their abstracts to the research questions. Finally, articles available for full access were selected, and their introduction, method, and results sections were examined for mentions of VR locomotion techniques and user feedback (e.g., ease of use, comfort, and performance). Additionally, relevant articles identified through citation tracking, often referred to as "snowball articles" [22], were also included.

B. *Article Analysis*

VR locomotion in the reviewed articles is analyzed qualitatively based on typology, rationale for selection, immersion features and requirements, and user experience. Typology, immersion quality, and user experience are categorized using variable approach, defined as "a measurement scale consisting of a set of categories" [23]. Thematic analysis, a systematic identification of patterns in data that serve as analytical categories [24], is used to examine the rationale behind the selection of locomotion methods. Themes selected as noun based on the underlying intention of each rationale (e.g., ease-of-use connotes convenience).

The type of locomotion is categorized using nominal variables based on Boletsis' typology (C, T, WiP, RDW). Locomotion methods not represented in this typology are classified according to the type that best characterizes their mechanical process. The analysis of immersion focuses on four key factors: (1) inclusivity, or the perception that locomotion in the virtual environment (VE) is unmediated, categorized as true or false; (2) extensiveness, or the range of sensory modalities engaged, categorized by the number of modalities present; (3) the alignment between body movement and sensory modalities, categorized as true or false; and (4) the presence of user embodiment within the virtual environment, also categorized as true or false.

User experience is assessed across three factors: usability, comfort, and performance. Each factor is categorized on an ordinal scale of low, moderate, and high.

IV. RESULTS

The search conducted on Google Scholar yielded 65 results, while ScienceDirect and SpringerLink listed 5 and 3 results, respectively. Using the PRISMA framework, as illustrated in Figure 1, the results were narrowed down to 14 articles for inclusion in the analysis. Additionally, one snowball article, identified through the references of a selected article, was added as it met all the identification and screening criteria.

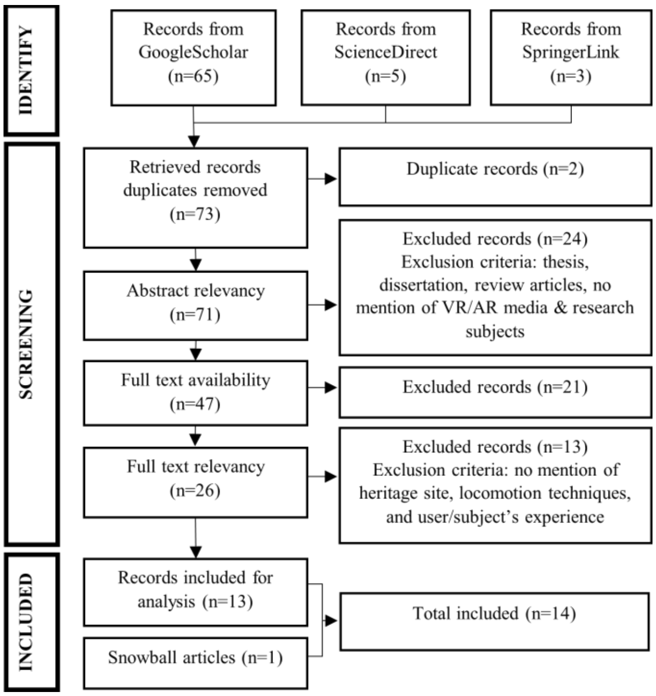

Figure 1. PRISMA framework for articles selection process

Table 1 provides analysis results for each article. The first article experimented with providing choice for user to select between menu-based (M), where user could move from one room to another by selecting the destination presented on a menu, or a combination of Teleportation (T) and Limited Walking (LW). LW is a walking-based locomotion technique restricted to a room-scale space, typically ranging from approximately 2m x 2m to 3.5m x 3.5m. Articles 7 and 8 allow users to choose between Controller (C) or Teleportation (T).

Nearly half of the reviewed articles (2-5, 7, & 12) does not stated the rationale for selection. Those that do mentioned considerations towards convenience for development (article 10 & 11) or user's convenience (article 9), experimenting with different approaches for a certain method (article 8), compare between choice of methods (article 1), explore approach to provide user with a better interface (article 13), and the freedom for navigating VE (article 6 & 14).

Immersion analysis provides a complete information for all reviewed articles, while the user's experience analysis is incomplete. Only article 1, 6, 7, 9, and 12 that provides the full recounts of all the aspects within the user's experience analysis.

V. DISCUSSIONS

The analysis indicates that controller-based methods, such as the C & T (Controller and Teleportation) technique, are predominantly employed for user locomotion when exploring heritage sites in virtual reality (VR). This preference is largely due to convenient factors. As suggested from several of the articles, C & T are the common locomotion methods that users are familiar with, as they are the default input devices in video game consoles or off-the-shelf VR application. Usability aspect in the analysis supports this findings, as it consistently favored by users. However, it is important to note that the reviewed articles do not include comparative studies with other locomotion modes, limiting the scope of this conclusion. VR content developers also favor controller-based methods, as these are often pre-integrated into game development software, making them more convenient for implementation and maintenance.

While walking-based methods, evaluated through immersion characteristics and user experience requirements, have the potential to enhance the sense of presence, Article 10 suggests that controller-based locomotion can deliver a comparable quality of presence when the controllers are integrated as embodied devices within the virtual environment (VE).

The findings suggest that controller-based methods are generally comfortable for users, with only a small number reporting motion sickness or dizziness. In contrast, the more natural walking-based approaches are perceived as less comfortable, as noted in Article 6.

Most articles report that users find the available locomotion techniques effective for exploring virtual heritage sites, though some (e.g., Articles 2, 3, 4, and 14) do not provide sufficient information to assess this fully.

VI. CONCLUSION

Visiting historical sites in VR can't substitute the authentic experience of physical visits. Nevertheless, VR has the capability to replicate the encounter to a certain extent. Walking-based locomotion in VR can more accurately replicate interaction within the physical world, upholding the historical site's place identity. Despite these benefits, studies indicate that most ongoing VR initiatives for historical sites favor the mediated strategy (controller-based).

Unmediated strategies are principally restricted to scholarly and research intentions. This inclination is attributed to the pragmatic and user-friendly nature of mediated methods; they do not necessitate users to move around and are recognizable to individuals through gaming. Unmediated methods, particularly RDW, necessitate increased computational capabilities to predict user motions, rendering them unfeasible for portable usage. It also requires user physical efforts that could contributes to user's fatigue and maybe contrary to user expectation that VR should provide convenience. However, these assumptions requires further investigation.

Nonetheless, advancements in spatial computing technology and the escalating prevalence of mobile gadgets with improved processing capabilities, coupled with increasing exploration in unmediated locomotion methods, might result in broader applications in the time to come. Subsequent studies in the creation of VR applications for exploring historical sites should integrate these locomotion methods to boost user's presence and elevate emotional engagement for historical site's place identity.

TABLE VI. VR LOCOMOTION ANALYSIS

Article	Type of Locomotion*	Rationale	Immersion				User's Experience		
			Inclusive	Modalities	Matching	Embodiment	Usability	Comfort	Performance
1	M / T + LW	experiment	false	2	true	false	high	high	high
2	C	n/a	false	2	false	false	n/a	n/a	n/a
3	C	n/a	false	2	false	false	n/a	high	n/a
4	C	n/a	false	2	false	false	n/a	low	n/a
5	T	n/a	false	2	false	false	high	n/a	high
6	WiP	experiment	true	2	true	true	low	low	high
7	C/T	n/a	false	2	false	true	high	low	high
8	C/T	experiment	false	2	false	false	high	n/a	high
9	C	convenience	false	2	false	false	high	moderate	high
10	C	convenience	false	2	true	true	n/a	n/a	high
11	C	convenience	false	2	false	true	high	n/a	high
12	T	n/a	false	2	false	false	high	high	high
13	RDW	experiment	false	2	true	false	n/a	n/a	high
14	WiP	experiment	true	2	true	false	n/a	n/a	n/a

*Controller (C), Teleport (T), Walk in Place (WiP), Redirected Walking (RDW), Limited Walk (LW), Menu-based (M)

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