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# Overcoming Topographical Barriers in Heritage Tourism: A Non-invasive Digital Twin and XR Framework for Inclusive Accessibility

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**Case Report**

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# Abstract

Balancing heritage authenticity with accessibility presents a "double constraint" for historical sites restricted by complex topography and strict preservation laws. This study addresses this challenge by proposing a non-invasive "Scan-to-Service" framework that integrates LiDAR, Digital Twin (DT), and Extended Reality (XR) to revolutionize inclusive smart tourism. Using Taipei's Treasure Hill Artist Village as a testbed, we developed a high-fidelity Digital Twin and an accessibility-optimized XR interface, subsequently validating the system's efficacy through the Task-Technology Fit (TTF) model with 36 elderly and mobility-impaired participants. Empirical results demonstrate that the virtual system significantly outperforms traditional physical tourism experiences. Notably, a surge in "Technology Utilization" scores confirms that such advanced tourism technology successfully unlocks latent demand previously suppressed by physical barriers, while business model analysis indicating a user preference for pay-per-use services suggests long-term economic sustainability. By establishing a comprehensive engineering workflow, this research theoretically extends the TTF model to the domain of inclusive heritage and demonstrates how automation can empirically realize spatial justice and cultural equity for marginalized groups.


# 1. Introduction

The global demographic structure is currently undergoing a significant transformation. According to the latest statistics from the World Health Organization (WHO), approximately 1.3 billion people—accounting for about 16% of the global population—face significant challenges related to disability (Ma et al. 2025), making them the world's largest marginalized group (2022a). Simultaneously, the global population aged 60 and over is projected to exceed 1.4 billion by 2030 (2022b). Studies show a high correlation between aging and disability, with approximately 46% of older adults experiencing physical function decline (James et al. 2018). However, when these groups attempt to engage in architectural heritage tourism, they often face severe "spatial exclusion." Data reveals that over 50% of individuals with mobility impairments abandon travel plans due to a lack of accessibility facilities (Darcy and Dickson 2009). This is particularly pronounced in cultural heritage sites bound by requirements of authenticity and irreversibility. Due to preservation regulations, original landscape features such as steep slopes, stairs, or narrow passages cannot easily be modified through traditional physical accessibility interventions like elevators or ramps (Liu et al. 2025). Consequently, historical sites ironically become exclusive spaces. Therefore, Therefore, balancing heritage preservation with the cultural participation rights of disadvantaged groups is critical in building information management and sustainable tourism (González-Herrera et al. 2023).

In recent years, the widespread application of Digital Twin (DT) and Extended Reality (XR) technologies has opened new avenues for architectural heritage preservation and endowed digital models with extended value (Funari et al. 2021; Furferi et al. 2024). Although Heritage Building Information Modeling (HBIM) has become a mainstream tool for cultural asset documentation(Pocobelli et al. 2018), and XR technology has matured in exhibition (Bekele et al. 2018; Sun and Ch'ng 2025), a significant gap remains

in the existing literature. Most research focuses on enhancing geometric fidelity or providing entertainment experiences for the general public(Mortara et al. 2014), rarely optimizing interfaces for the the elderly and mobility-impaired (Dore and Murphy 2014; Ijaz et al. 2022). Neglecting these needs risks creating a new digital divide (Huygelier et al. 2019; Chen et al. 2024).

The objective of this study is to construct a virtual tourism system integrating DT and XR technologies, utilizing the digital turn to break through physical limitations. This study selects *Taipei Treasure Hill Artist Village*, known for its complex topography, as the empirical site. By introducing adaptive voice guidance, high-contrast visual aids, and simplified interaction logic (Zhang et al. 2025), this study transforms passive viewing into an active, barrier-free virtual participation experience (Xie et al. 2026). To verify the system's effectiveness, this study adopts the Task-Technology Fit (TTF) model as its theoretical basis (Goodhue and Thompson 1995), distinguishing itself from previous research paths that focus solely on “Technology Acceptance” (Wang and Men 2025). This study argues that the key lies in the fit between the functional characteristics of the digital guide system and the physical and mental needs of elderly tourists. Through quantitative questionnaires and actual user feedback, this study evaluates the system's operational fluency, immersion, and psychological involvement (Yan et al. 2025). Furthermore, it investigates participants' willingness to pay for virtual tourism services to verify the potential of future business models (Lai et al. 2025). This research is expected to expand the application scope of BIM from engineering operations to social behavioral science(Shang et al. 2025).

While technologies such as LiDAR scanning and VR engines are commercially available, the primary contribution of this study lies in establishing of a novel “Scan-to-Service” workflow tailored for heritage sites facing the double constraint of complex topography and strict preservation regulations (Wu et al. 2026). By integrating these tools into a cohesive framework validated by the TTF model, this study provides a scalable engineering solution for overcoming “physical exclusion” (Milligan 2013). This moves beyond mere digital archiving to create a functional, inclusive service model that can be replicated at other heritage sites worldwide where physical accessibility modifications are prohibited.

## 2. Literature Review

# 2.1 Comparison between Virtual and Traditional Tourism

With the rapid evolution of DT and XR technologies, tourism research has expanded from physical mobility to virtual experiences (Guttentag 2010). Virtual tourism effectively transcends spatiotemporal limitations. Through highly immersive interfaces, it allows users to achieve a sense of "Telepresence" without physical travel costs (Tussyadiah et al. 2018). Regarding physical accessibility, traditional tourism relies heavily on tourists' physical capabilities and geographic accessibility, creating significant entry barriers for the elderly and mobility-impaired (Chi et al. 2023). Conversely, virtual tourism eliminates physical obstacles and uncertainties related to the external environment (e.g., climate, rugged terrain). In health restriction contexts, the intention to adopt virtual tours is significantly higher than that for physical tours, demonstrating its value as an alternative tourism solution (Itani and Hollebeek 2021).

In terms of psychological cognition and experiential marketing, although virtual tourism cannot fully replace the multisensory experience of on-site visits, it possesses unique advantages in information dissemination efficiency and emotional priming. Empirical studies indicate that compared to traditional 2D media, XR technology can significantly enhance potential tourists' emotional experiences and their perception of the destination's image, thereby reinforcing future intentions to visit physically (Lin et al. 2020). From the perspective of environmental sustainability and social responsibility, virtual tourism is characterized by low carbon emissions and minimal physical interference. Ecological presence within virtual environments can strengthen users' environmentally responsible attitudes, making it an effective medium for promoting sustainable tourism and environmental education (Su et al. 2024; Ljubisavljević et al. 2025).

In summary, traditional tourism is irreplaceable for authenticity, whereas virtual tourism demonstrates superiority in accessibility, risk avoidance, and information augmentation. For the mobility-impaired, virtual tourism provides a critical equal participation mechanism ([CSL STYLE ERROR: reference with no printed form.]).

## 2.2 Application Benefits of Extended Reality in Tourism for the Elderly and People with Disabilities

XR, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), is a pivotal tool for enhancing the quality of life and leisure participation of the elderly and individuals with disabilities(Juan et al. 2022; Crogman et al. 2025). Physiologically and cognitively, immersive XR tourism provides elderly individuals with sensory experiences akin to physical visits within a safe and controlled environment, thereby fostering cognitive stimulation. For instance, researchers have developed VR bicycle tourism systems integrating 360-degree panoramic imagery, allowing seniors to engage in virtual cycling (Tegegne et al. 2025). These systems serve as destination marketing tools and significantly enhance users' willingness for physical activity and psychological well-being (Ortet et al. 2022). Regarding interactivity and user experience (UX), studies indicate that compared to passive 360-degree video viewing, the elderly exhibit a significant preference for VR environments with high interactivity and presence (Pei et al. 2023; Shim et al. 2024). Active exploration via gestures or controllers endows users with a heightened sense of perceived control, thereby improving mental health indicators and overall satisfaction (Kupczik et al. 2022).

## 2.3 Analysis of Point Cloud and Digital Twin Technology Applications

Point cloud technology serves as a fundamental basis for the digitization of cultural heritage (Storeide et al. 2023). Integrating digital photogrammetry and Terrestrial Laser Scanning (TLS) allows for complete documentation of the geometric morphology and surface details of cultural assets in a non-invasive manner (Markiewicz et al. 2023), facilitating preservation and research (Yastikli 2007; Calvo-Serrano et al. 2022). Combining TLS with Unmanned Aerial Vehicle (UAV) imagery to establish 3D digital models demonstrates the practical feasibility of point cloud technology in surveying large-scale cultural assets

(Jo and Hong 2019). Such studies reveal that point cloud technology has evolved from a recording tool into a core data source supporting dynamic digital reflections that mirror physical assets through sensor integration (Maria Skublewska-Paszkowska et al. 2022; Albertini et al. 2022).

Originating in the aerospace and manufacturing sectors, DT technology constructs digital mirror systems characterized by real-time data synchronization, dynamic updates, and high-fidelity interaction. Applied across the architecture and tourism industries, physical scenes are transformed into visualizable virtual environments through high-precision spatial scanning and real-time sensing technologies (Tang et al. 2019; Boje et al. 2020). Furthermore, when DTs are combined with BIM, they form a comprehensive “Smart Spatial Platform”.

The virtual world constructed by DTs requires XR as the Human-Computer Interaction (HCI) interface to provide users with immersive experiences. According to the “Reality-Virtuality Continuum” theory proposed by Milgram (Milgram and Kishino 1994), XR encompasses a continuous spectrum ranging from the completely real to the completely virtual. Applying this theoretical framework to barrier-free tourism ensures the most appropriate intervention mode is selected based on the physiological limitations of users and device accessibility.

## 2.4 Analysis of Task-Technology Fit (TTF) Verification Model

The Task–Technology Fit (TTF) model, proposed by Goodhue and Thompson (1995) (Goodhue and Thompson 1995), posits that information technology enhance system utilization only when its functional characteristics align precisely with the user’s task requirements. The original model suggests that "Task Characteristics" and "Technology Characteristics" jointly influence the user's perception of fit. Goodhue and Thompson subsequently developed the TTF scale to evaluate whether information systems truly support users to complete tasks, transcending subjective “perceived ease of use”. Unlike general tourism where entertainment is the sole goal, heritage tourism involves learning and experiencing tasks, making TTF a more suitable model than pure hedonistic models.

In this study, the task requirements for elderly and mobility-impaired individuals engaging in architectural heritage tourism include: accessing historical environments with safety and low physiological load, retrieving architectural and cultural information, autonomously regulating pacing based on physical condition, and reducing uncertainty regarding unfamiliar spaces and mobility risks. Conversely, the virtual tourism system constructed in this study possesses specific technology characteristics, such as high-immersion visuals, simplified barrier-free navigation interfaces, real-time information accessibility, and pre-visit preview functions.

# 3. Development of Virtual Tourism Guidance System

## 3.1 Virtual Tourism Construction: Site Selection and Characteristics

This study selects the *Taipei Treasure Hill Artist Village*, the first registered “Historical Settlement” in Taipei, as the experimental validation site (as shown in Fig. 1). Formally registered under the Cultural Heritage Preservation Act in 2004, it preserves the unique self-built organic architectural fabric of the post-war immigrant society and a social landscape characterized by the symbiosis of artistic practice and residential living, possessing irreplaceable cultural conservation value.

However, the settlement's morphology along steep river terraces created a maze-like aesthetic of staggered stairs and narrow alleys. Due to the “irreversibility” mandates of legal cultural heritage protection, traditional accessibility interventions (e.g. ramps or elevators) cannot be implemented without compromising the historical integrity (Kruczek et al. 2023). For the elderly and mobility-impaired, this vertical topography increases the risk of falling and creates severe spatial exclusion, strictly limiting their on-site visits. Consequently, this site serves as an ideal and representative testbed for verifying virtual tourism as an alternative solution to physical visits.

## 3.2 Framework of Virtual Tourism System Construction

As illustrated in Fig. 2, the construction process of the virtual tourism system is divided into four phases. The workflow progresses from on-site data acquisition to DT modeling and HCI integration:

- On-site Investigation and Data Acquisition: Documenting the overall spatial topology, gradient variations, and key landmarks through field surveys using high-resolution cameras and 3D laser scanning. Special attention is given to “critical nodes” that affect the mobility of individuals with disabilities—such as stairs, narrow alleys, and elevation transitions—to ensure these physical barriers are accurately digitized.
- Point Cloud Processing and DT Modeling: Raw point cloud data is processed through noise filtering, multi-station registration, and accuracy verification. Based on the consolidated 3D point cloud of the entire site, reverse modeling converts the data into a DT model endowed with geometric details and material textures, encompassing main architectural volumes, pathways, stair structures, plazas, and surrounding environmental elements.
- Virtual Scene Construction and Interaction Design: The completed DT model is imported into a VR engine. The scene planning and path design are tailored for the elderly and mobility-impaired. Key design elements include the implementation of intuitive visual navigational nodes, the integration of multimedia information interfaces (text/audio), and the configuration of locomotion mechanics specifically designed to mitigate visually induced motion sickness and enhance operational intuitiveness.
- XR Device Integration and Experience Optimization Phase: The system is integrated with immersive devices (Meta Quest 3). This phase focuses on performance tuning and interface optimization, including testing for visual quality, frame rate stability, and interaction feedback. The operational

flow and dwell rhythm are fine-tuned according to the physiological and cognitive characteristics of the elderly for a safe and controllable experience.

## 3.3 System Architecture and Interface Development

This study constructs a virtual tourism system based on a three-tier architecture, as shown in Fig. 3. First, the “Data Layer” integrates high-precision point cloud scanning data with on-site accessibility survey parameters, thereby establishing a digital base map characterized by geometric fidelity. Second, the “Processing Layer” executes core computational tasks, including point cloud registration, mesh decimation, anti-sickness interaction algorithms, and path smoothing tailored to elderly users. Finally, the “Application Layer” transforms complex backend computations into an intuitive immersive experience through a VR interface with adaptive visual aids and audio guidance.

## 3.4 Instrumentation and Software for Point Cloud Scanning

While traditional TLS instruments (e.g., Faro Focus series) offer superior measurement accuracy, they are often bulky, time-consuming to set up, and lack the mobility required for complex terrains. For virtual tourism, visual fidelity and spatial topology are prioritized over sub-millimeter structural engineering accuracy. Consequently, this study utilizes the Matterport Pro 3 3D Capture System equipped with LiDAR technology as the primary tool for point cloud data acquisition (Fig. 4). This device integrates 360-degree panoramic photography with LiDAR depth sensing for simultaneous acquisition of RGB imagery and depth information.

This equipment was selected for its high adaptability to *Treasure Hill*’s extreme spatial constraints (some only wide enough for a single person) and drastic elevation changes (frequent stairs and steep slopes), making traditional surveying equipment unfeasible. Its lightweight mobility allowed rapid 3D documentation of the large-scale site with optimized time and labor costs.

Scanning operations were controlled via a mobile device using the Matterport Capture application. Scan stations were sequentially deployed along the main pedestrian circulation routes, nodal spaces, and key landmarks of *Treasure Hill Artist Village* (e.g., the temple plaza, settlement entrance, and viewing platforms). Based on on-site geometric scales, the distance between adjacent scan points was strictly controlled to ensure a sufficient overlap ratio to prevent registration errors. Upon completion of on-site scanning, raw data was uploaded to the Matterport Cloud Platform for automated processing, including image stitching, feature matching, and 3D mesh reconstruction, generating high-density point cloud data (Fig. 5). The model was then exported for further mesh decimation, texture optimization, and coordinate adjustment in the VR development environment.

## 3.5 Virtual Reality Display System and Interactive Interface

This study adopts the Meta Quest 3 VR Head-Mounted Display for its standalone computing capability and high-resolution display. Regarding hardware safety and accessibility, its untethered configuration

eliminates tripping hazards caused by cables, providing a safer and more flexible experimental environment for participants with mobility impairments. The device supports Six Degrees of Freedom (6DoF) spatial tracking for immersive exploration. To optimize physiological adaptation, considering that the elderly and mobility-impaired individuals may have heightened sensitivity in their vestibular systems, this study strictly calibrated system parameters to mitigate "Cybersickness". The research team maintained the frame refresh rate at a stable 90Hz or above to minimize motion-to-photon latency. Furthermore, locomotion speeds and dwell rhythms were optimized to prevent excessive optical flow from inducing dizziness. The display system and interactive interface are illustrated in Fig. 6. These optimizations ensure the comfort and operability of the virtual tourism experience, establishing a stable technical foundation for subsequent TTF evaluation.

## 4. Research Design

# 4.1 Instrument Development and Experimental Procedure

This study develops its assessment instrument based on the TTF model. The core objective is to verify whether the virtual tourism system constructed in this research offers a superior solution to the pain points of the elderly and mobility-impaired compared to their traditional tourism experiences.

Regarding the experimental design, a within-subjects design was employed. Participants were first asked to recall and evaluate their past experiences with traditional physical tourism. Subsequently, they engaged in a 30-minute immersive virtual tour of Treasure Hill Artist Village using the Meta Quest 3 headset. Upon completion, participants responded to a questionnaire covering the five dimensions of the TTF model. Paired-samples t-tests were used to analyze the data and examine the differences in means between the two tourism modes. A significantly higher score for virtual tourism would empirically validate its superior technological fit for the target demographic.

The questionnaire utilized a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). To ensure content validity, items for each construct were adapted from the original TTF scale and contextually refined based on literature regarding cultural heritage and accessible tourism. The operational definitions are as follows:

- Task Characteristics: Refers to the activities and challenges users face during cultural heritage tourism, including the needs to overcome topographical barriers, access guide information, and ensure mobility safety.
- Technology Characteristics: Refers to the functional attributes of the tourism medium (physical or virtual), including visual clarity, interface usability, environmental immersion, and device safety.
- Task–Technology Fit: Refers to the degree to which the technology effectively supports the execution of tourism tasks; specifically, the alignment between system functionality and accessible tourism requirements.

- Technology Utilization: Defined in this experimental context as the user's intention and propensity to adopt this virtual system as an alternative or supplementary tool for future tourism.
- Performance Impact: Refers to the enhancement in the quality of the tourism experience following technology use, including increased satisfaction, efficiency in acquiring cultural knowledge, and improvements in psychological relaxation and enjoyment.

# 4.2 Participants and Experimental Procedure

This study employed a purposive sampling strategy, recruiting a total of 36 participants comprising the elderly and individuals with mobility impairments. The inclusion criteria were as follows: (1) Aged 65 or older, or possessing an official disability certificate; (2) Possessing adequate cognitive and communicative capacities; and (3) Having prior negative experiences or difficulties participating in traditional physical tourism. All participants signed an Informed Consent Form prior to the experiment, ensuring compliance with research ethics.

Given the high-risk characteristics of the experimental site—such as steep topography, frequent stairs, and slippery surfaces—compelling mobility-impaired participants to perform an on-site control experiment would pose severe safety hazards and ethical concerns. Consequently, due to these ethical constraints, this study could not adopt a simultaneous on-site control design. Instead, a retrospective comparison approach was adopted, where participants used their past traditional tourism experiences as the baseline. The objective was to investigate the quantitative differences in technological fit, task support, and psychological perception following the virtual tourism intervention.

The experiment was conducted via a one-on-one guided mode to ensure data credibility and participant safety. A quiet, spacious, and well-lit indoor laboratory was selected to minimize external disturbances. The procedure began with an explanation of the workflow and risk disclosure. Subsequently, researchers assisted participants in fitting the Meta Quest 3 headset, adjusting the strap tightness and interpupillary distance according to individual visual conditions to ensure visual clarity and comfort. The duration of the virtual tourism experience was set at 30 minutes. Considering the physiological characteristics of the participants, researchers monitored the process in real-time to detect any signs of cybersickness or physical discomfort (experimental process shown in Fig. 7).

## 5. Results Analysis

# 5.1 Reliability Analysis

To assess the reliability of the measurement instrument, this study utilized Cronbach’s α coefficient to examine the internal consistency of each construct. The analysis results indicate that the Cronbach’s α values for all five constructs exceeded 0.8 (surpassing the generally accepted threshold of 0.7), demonstrating that the questionnaire possesses excellent reliability and high consistency. Overall, the

measurement instrument exhibits high stability and reproducibility, serving as a reliable basis for subsequent statistical inference and hypothesis testing.

## 5.2 Paired-Samples t-Test and Hypothesis Verification

This study also employed a paired-samples t-test to examine the significance of differences in participant perceptions between the virtual tourism experiences and their past traditional tourism experiences. The results of the test are presented in Table 1.

Table 1
Results of the paired-samples t-test

| Construct | Tourism Mode | Mean (M) | SD | t-value | p-value |
|---|---|---|---|---|---|
| Task Characteristics | Traditional | 3.493 | 0.936 | -3.248 | .003 |
| | Virtual | 4.000 | | | |
| Technology Characteristics | Traditional | 3.333 | 0.685 | -6.628 | < .001 |
| | Virtual | 4.000 | | | |
| Task-Technology Fit | Traditional | 3.463 | 0.779 | -4.705 | < .001 |
| | Virtual | 4.074 | | | |
| Technology Utilization | Traditional | 3.138 | 0.698 | -10.797 | < .001 |
| | Virtual | 4.396 | | | |
| Performance Impact | Traditional | 3.550 | 0.859 | -2.793 | .008 |
| | Virtual | 3.950 | | | |

Although the sample size (N = 36) was constrained by the inherent difficulty of recruiting specific vulnerable populations, the statistical results revealed that differences across all constructs reached statistical significance at the 95% confidence level ($p < 0.05$). Specifically, the virtual tourism system significantly outperformed traditional tourism experiences in terms of mean scores across all five dimensions: “Task Characteristics”, “Technology Characteristics”, “Task-Technology Fit”, “Technology Utilization”, and “Performance Impact”. The analysis demonstrated a large effect size indicating that the magnitude of the difference between virtual and traditional experiences is robust. That is, these empirical results confirm that the proposed virtual tourism system effectively overcomes physical barriers and significantly enhances engagement and experiential satisfaction for the elderly and mobility-impaired.

# 6. Discussion

## 6.1 Explaining the Superiority of Virtual Tourism through TTF

The statistical data in Table 1 provides compelling empirical evidence that the virtual tourism system significantly outperforms traditional tourism across all TTF dimensions. First, regarding the core construct of “Task-Technology Fit”, the mean score significantly increased from 3.463 in the traditional mode to 4.074 in the virtual mode ($t = -4.705$, $p < 0.001$). This result illuminates a key finding: for the elderly and individuals with mobility impairments, the lower scores in traditional tourism stem not from a lack of interest in cultural content, but from a severe misalignment between task requirements (e.g., navigating steep terrains) and physical capabilities. The virtual tourism system, through its digital twin geometric reconstruction and accessible locomotion mechanics, successfully bridges this gap, achieving a significantly higher degree of fit.

Notably, the “Technology Utilization” construct exhibited the most profound statistical difference, with a t-value of -10.797 and the mean score surging from a neutral 3.138 to a highly positive 4.396. This massive effect size suggests a substantial latent demand for accessible tourism among the target demographic. In the traditional mode, user participation was suppressed by the physical barriers of Treasure Hill Artist Village (corroborated by the lower "Technology Characteristics" score of 3.333). The intervention of the VR system (raising Technology Characteristics to 4.000) effectively unlocked this suppressed demand.

Furthermore, regarding “Performance Impact”, the significant difference ($p = 0.008$) confirms that virtual tourism serves not merely as a substitute, but substantially enhances the quality of the cultural experience. This finding challenges previous literature suggesting that virtual experiences lack authenticity and thus reduce satisfaction.(Mura et al. 2017) (Yang et al. 2023) Conversely, for elderly and mobility-impaired groups, accessibility is the prerequisite for performance. This study demonstrates that removing physical obstructions through digital technology is the unique and necessary pathway to enhancing tourism performance for this specific demographic.

## 6.2 Commercial Implications and Sustainable Operation Models

Beyond technical validation, this study investigated the commercial potential of virtual tourism services to assess the feasibility of long-term system operation. The analysis reveals a significant trend in business model preferences: both the elderly and mobility-impaired groups demonstrated a strong preference for a “Pay-per-use” model over a "Subscription-based" model. This reflects a consumer inclination towards low-commitment and high-flexibility consumption patterns regarding emerging technology services.

However, regarding the specific range of Willingness to Pay (WTP), the two groups exhibited distinct value perceptions. The data indicates that mobility-impaired users have a higher WTP, with an average

acceptable price for a single session ranging between NT$ 100 and 500 (and NT$ 2,000–3,000 for monthly subscriptions). This suggests that for this demographic, virtual tourism addresses a rigid demand—accessing inaccessible sites—thereby possessing high functional value. Conversely, the elderly group exhibited significantly higher price sensitivity, with their single-session WTP primarily falling between NT$ 0 and 100 (and as low as NT$ 0–1,000 for monthly subscriptions), indicating they may view this primarily as a leisure-oriented supplementary service. The low WTP of the elderly suggests that a pure commercial model may be challenging, and a Public-Private Partnership (PPP) model might be more suitable.

These discrepancies highlight the necessity of implementing a differentiated pricing strategy when promoting inclusive digital experiences. Future operational models are suggested to offer high-value, in-depth guided services for individuals with severe mobility impairments, while adopting a low-cost penetration strategy for the general elderly population. Such a hybrid business model would help support the ongoing maintenance and update costs of the DT database, thereby achieving both technological and commercial sustainability.

## 6.3 User Feedback from Mobility-Impaired and Elderly Participants

Based on the operational feedback and interviews with the participants, this study summarizes two critical findings regarding user needs and system optimization. First, participants expressed a strong desire for the expansion of virtual content. Due to physical limitations, they are often unable to undertake long-distance travel or navigate complex terrains. Consequently, they hope the system can transcend geographical boundaries, extending the experience to international heritage sites or landscapes with high physical accessibility barriers. This feedback confirms that virtual tourism serves as a vital medium for spatial extension, allowing users to explore unknown environments and fulfilling the goal of digital cultural equity. Second, regarding the issue of digital dizziness (cybersickness) frequently reported by elderly users, feedback indicates that visual clarity and fluidity are critical factors affecting the experience. This implies that future system development must prioritize the optimization of high-resolution textures and the reduction of system latency. Mitigating these physiological discomforts is essential for constructing a barrier-free digital environment that is not only aesthetically pleasing but also comfortable for long-term use.

## 6.4 The Potential of Integrating Digital Twin, HBIM, and XR

This study demonstrates the synergistic potential of integrating DT, HBIM, and XR through the empirical case of Treasure Hill. Traditional cultural heritage conservation often focuses on static geometric recording (e.g., point cloud archiving) or professional-oriented information management (e.g., HBIM), creating an information gap that hinders public understanding of heritage values. The integrated framework proposed in this study successfully bridges this gap.

The integration of DT and HBIM endows the point cloud model with semantic enrichment, transforming unstructured point cloud data into object-oriented models enriched with attribute data (e.g., construction period, material composition, historical narratives). XR serves as the pivotal Human-Computer Interface (HCI) that translates complex engineering data for end-users. For individuals with mobility impairments, XR removes physical barriers to access; for the general public, it transforms dry BIM data into vivid, immersive experiences. While traditional DTs often emphasize real-time sensor data, this study proposes a 'Semantic Digital Twin' model tailored for heritage accessibility. The bidirectional flow is established not through automated sensors, but through human-in-the-loop validation. The VR system acts as a simulation tool where user feedback (“Task-Technology Fit” scores and qualitative responses) serves as critical input data. This data allows managers to identify accessibility blind spots within the digital model, updating the semantic information of the DT (e.g., reclassifying certain paths as non-navigable for the elderly). Thus, the system successfully bridges the gap between virtual simulation and physical management strategies.

# 7. Conclusion

With the advent of a global aging society, balancing the "authenticity preservation" of architectural heritage with accessibility has become a critical challenge in the fields of construction automation and heritage management. This study utilized the Treasure Hill Artist Village—a site characterized by complex topography and strict regulatory constraints—as a testbed to successfully construct a virtual tourism framework integrating LiDAR, DT, and XR. This framework demonstrates that digital technology can serve as an effective non-invasive auxiliary solution to overcome spatial exclusion in physical environments without requiring destructive engineering interventions.

Regarding theoretical validation, this study applied the TTF model for empirical analysis. Paired-samples t-test results indicate that the virtual tourism system significantly outperforms participants' past traditional tourism experiences across constructs such as "Task Characteristics", "Technology Characteristics", and "Technology Utilization". Notably, the substantial surge in the "Technology Utilization" score reveals a massive latent demand for cultural participation among the elderly and mobility-impaired, which was previously suppressed solely by physical barriers. This study confirms that as long as technology characteristics precisely fit users' physical and mental limitations (e.g., providing anti-sickness locomotion mechanics), the elderly demonstrate high acceptance and capability in operating immersive technologies.

In terms of practical and engineering implications, this study proposes a comprehensive workflow from point cloud surveying to service application (Scan-to-BIM-to-VR). This extends the value of BIM from traditional design, construction, and facility management to the realm of social service and human-centric experience. Furthermore, the investigation into business models suggests that through a differentiated pay-per-use strategy, virtual tourism possesses the potential to develop into a sustainable operational model, generating additional revenue for heritage maintenance.

While this study has validated the effectiveness of visual and auditory experiences, limitations remain regarding the lack of haptic feedback and multimodal sensory interaction. Future research is suggested to further integrate generative AI guides to provide adaptive conversational services and to incorporate real-time physiological sensing technology to dynamically adjust virtual environmental parameters. These advancements aim to construct a smart, accessible tourism ecosystem characterized by high empathy and adaptability.

## Declarations

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# Author Contribution

Y.K. Juan conceptualized the research, wrote the main manuscript text, and validated the results. S.Y. Chuang co-wrote the main manuscript text, conducted the site investigations, administered the questionnaires, and developed the XR system. H.Y. Chi supported the XR system development, contributed to the methodology, conducted the experiments, and provided technical support. Y. Xu contributed to the literature review, assisted with the experiments, and performed the data analysis of the questionnaire results. All authors reviewed and approved the final manuscript.

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# Figures



**Figure 1**

Alleyways of Treasure Hill Artist Village

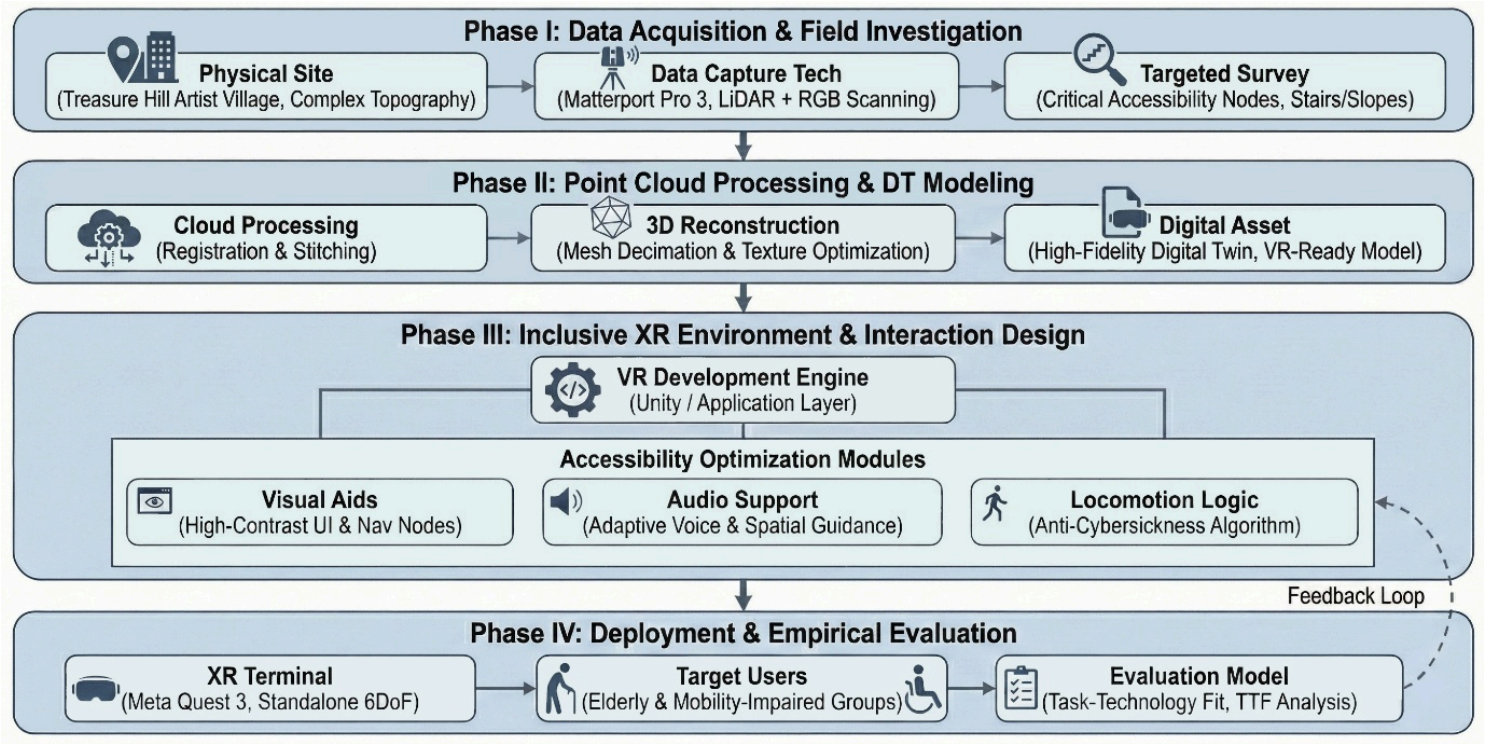



**Figure 2**

Framework of virtual tourism system

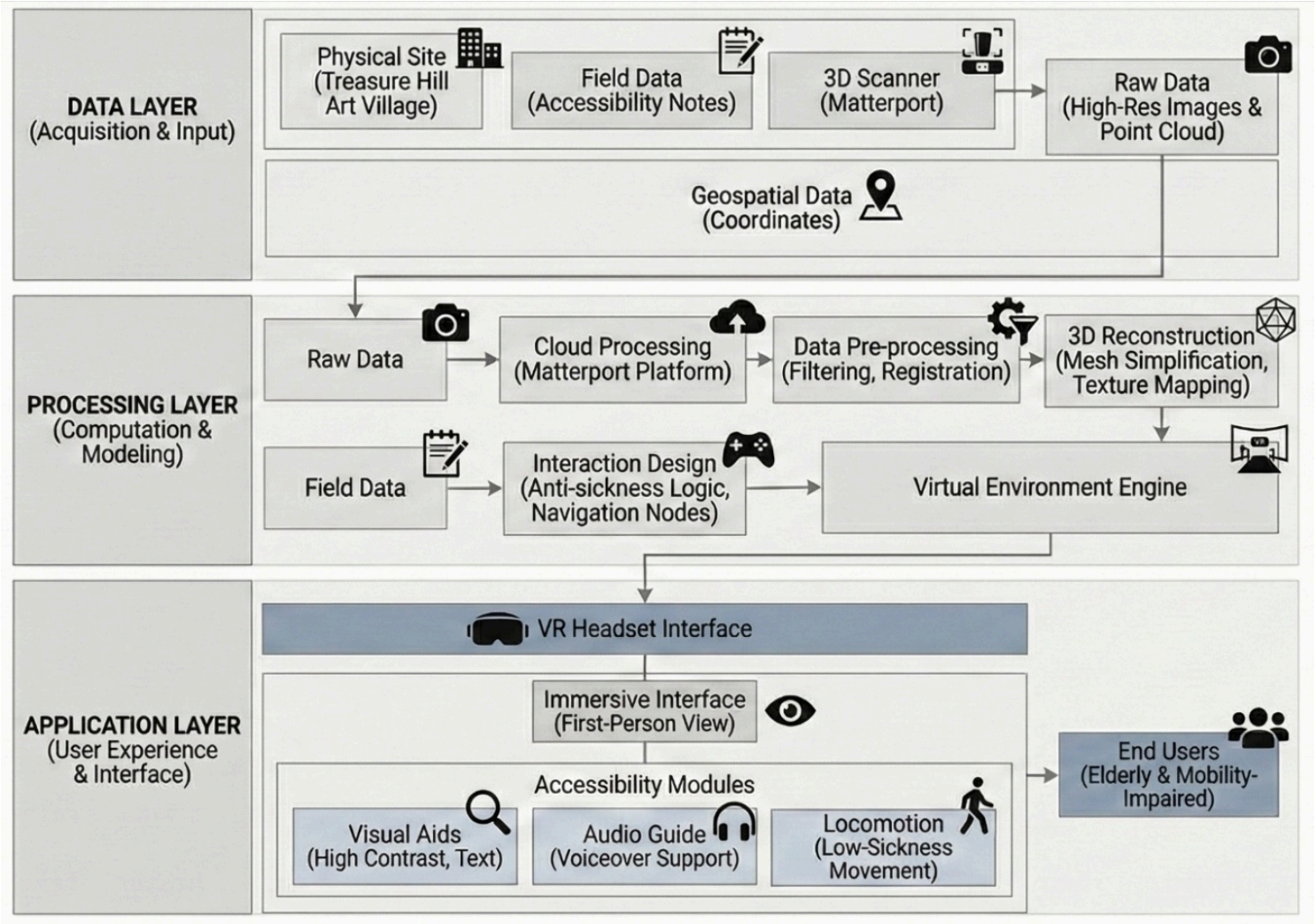



**Figure 3**

System Architecture



**Figure 4**

On-site inspection and Matterport Pro 3 3D scanning

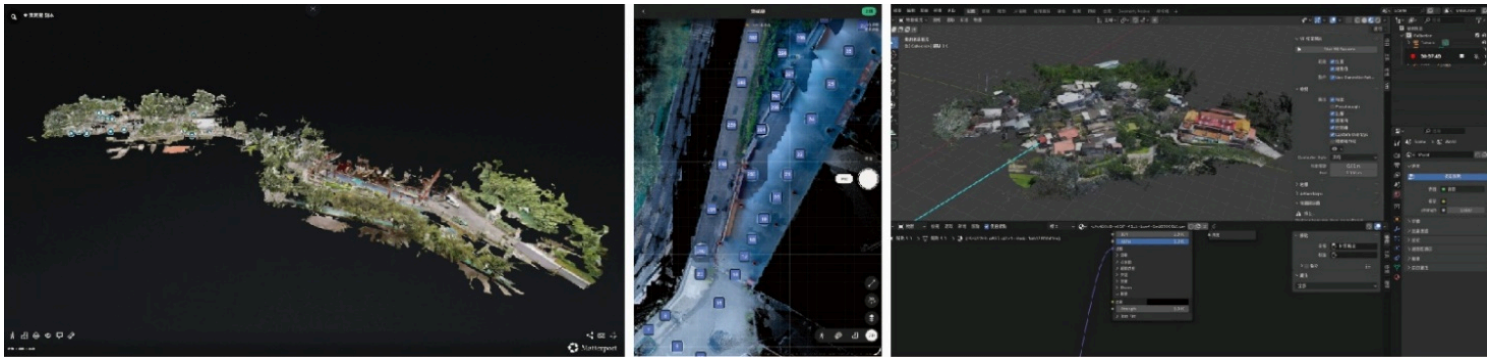


**Figure 5**

Matterport results



**Figure 6**

Display system and interactive interface



**Figure 7**

Experimental process for the elderly and mobility-impaired