

Design and Evaluation of a 13K Ultra-High-Resolution Web-Based Virtual Reality Platform for Immersive Spatial Visualization

Worapon Manosroi, Apisak Phromfaiy*, Pitak Khlaichom

Faculty of Industrial Technology, Uttaradit Rajabhat University, Uttaradit, 53000, Thailand

Abstract—Delivering ultra-high-resolution immersive environments via standard web browsers presents significant rendering and architectural challenges. While Virtual Reality (VR) is widely adopted, its application as a high-fidelity spatial visualization tool often lacks robust empirical evaluation regarding user experience and system efficacy. This study proposes the design, development, and evaluation of a 13K ultra-high-resolution web-based virtual tour platform, utilizing a nature-based destination as a practical case study to assess system effectiveness. The system architecture was engineered to process and render 13K panoramic data with interactive navigational hotspots, ensuring cross-platform web compatibility. To evaluate the Human-Computer Interaction performance, a true experimental design was employed with eighty participants who were randomly assigned to two groups. The experimental group interacted with the proposed 13K web-based platform, while the control group utilized a conventional static two-dimensional web interface. System efficacy was measured through user-centric metrics, including Sense of Presence, spatial image perception, and subsequent behavioral intention. The evaluation results demonstrated a statistically significant superiority of the proposed 13K platform. Users reported a substantially higher Sense of Presence score of 4.35 out of 5, compared to the conventional web interface score of 2.45. Furthermore, the immersive system architecture significantly catalyzed positive spatial perception and behavioral engagement, yielding a remarkably large effect size. The findings validate that the proposed high-fidelity web-based VR architecture effectively overcomes physical barriers, serving as a highly effective information system solution for remote spatial visualization and practical destination management.

Keywords—Virtual Reality; 360-degree panorama; web-based platform; immersive spatial visualization; ultra-high-resolution panorama; HCI (Human-Computer Interaction)

I. INTRODUCTION

In the era of digital transformation, the integration of immersive technologies—particularly Virtual Reality (VR) and 360-degree panoramic imaging—into web-based platforms has revolutionized spatial visualization [5, 22]. Unlike traditional standalone VR applications that require specialized, high-cost hardware and heavy client-side processing, Web-based VR democratizes access to immersive content by utilizing standard internet browsers [1, 3]. This technological shift is increasingly critical across various industrial and managerial sectors, including urban planning, real estate, and destination management, where high-fidelity spatial representation is

required to digitally bridge the geographical distance between the user and the physical environment [9, 23].

However, delivering ultra-high-resolution immersive environments, such as 13K panoramas, through standard web infrastructures presents substantial architectural and computational challenges. Conventional static media (e.g., 2D photographs and text-based websites) are categorized as "lean media", which demand minimal bandwidth but offer limited sensory engagement, often failing to convey the atmospheric depth and spatial magnitude of complex environments [2]. Conversely, deploying "rich media" at a 13K resolution generates massive datasets that require optimized data processing, efficient cloud storage, and robust rendering engines (e.g., WebGL) [17, 18]. Without proper system architecture, delivering such massive spatial data over the web often results in severe latency, bandwidth bottlenecks, and frame-rate drops. These technical degradations fundamentally disrupt the Human-Computer Interaction (HCI) experience, breaking the illusion of "telepresence"—the critical subjective sensation of being physically present in a remote digital environment [13, 16].

To systematically evaluate how system engineering directly influences user psychological states, this study adapts the Stimulus-Organism-Response (S-O-R) model through an HCI perspective [6]. In this context, the "Stimulus" is defined as the system's technological affordances—specifically, the media richness, interactive navigational UI, and the 13K ultra-high visual fidelity [1, 3]. The "Organism" represents the user's cognitive and affective processing during system interaction, primarily operationalized as the "Sense of Presence" [4, 25]. Finally, the "Response" constitutes the user's behavioral outcomes, system evaluation, and future adoption readiness [1, 8, 20]. This approach allows for a precise empirical measurement of the system's efficacy.

To address these technical limitations and evaluate the proposed framework, this study introduces a robust information system architecture for a 13K web-based virtual tour platform [24, 26]. To empirically validate the system's effectiveness and real-world applicability, the domain of seasonal destination management—specifically the Tha Pla District in Uttaradit, Thailand—was selected as a practical case study. Nature-based environments that face severe physical access constraints (e.g., hydrological closures during monsoons) provide an ideal, complex scenario to stress-test the system's capacity to serve as a high-fidelity digital "substitution tool" [7].

*Corresponding author

Therefore, the primary objectives of this research are twofold: 1) to design and develop a cloud-based, 13K ultra-high-resolution web VR architecture capable of smooth, interactive rendering across standard devices, and 2) to empirically evaluate the system's HCI performance—specifically its impact on Sense of Presence, spatial image construction, and behavioral intention—against conventional static web interfaces [20, 28]. By doing so, this study contributes to the advancement of applied computer science in scalable spatial visualization systems.

Unlike conventional web-based VR platforms that frequently encounter processing bottlenecks and rendering latency when handling massive textures, the proposed 13K ultra-high-resolution architecture utilizes a dynamic tiling algorithm. This approach significantly reduces server load, memory usage, and rendering overhead, thereby offering a notable and highly scalable improvement in immersive spatial visualization over existing web-VR baseline systems.

II. RELATED WORK

To contextualize the contributions of this study within the broader landscape of applied computer science and spatial visualization, this section reviews the foundational literature across three distinct domains: web-based immersive systems, rendering optimization algorithms, and Human-Computer Interaction in virtual environments.

A. Evolution of Web-Based Spatial Visualization:

The paradigm of spatial visualization has fundamentally shifted from native, hardware-dependent applications to ubiquitous web-based platforms. Traditionally, delivering high-fidelity Virtual Reality (VR) required dedicated client-side software and powerful Graphical Processing Units (GPUs) [5, 27]. However, the advent of WebGL and HTML5 standards has enabled browsers to natively render complex 3D and panoramic environments. Ali et al. [9] emphasized that web-based spatial digital twins are becoming the standard for remote monitoring, urban planning, and industrial facility management due to their inherent cross-platform accessibility. Despite this shift, as Rosli et al. [21] noted, the majority of current web VR platforms still rely on low-to-medium resolution imagery (e.g., 4K or 8K) to ensure smooth delivery, thereby sacrificing environmental realism. Bridging the gap between ubiquitous web access and ultra-high-fidelity (13K and beyond) remains a critical open challenge in spatial computing.

B. Rendering Optimization and the 13K Challenge:

Delivering massive spatial datasets over standard HTTP/HTTPS protocols introduces severe bandwidth and latency bottlenecks. A standard 13K equirectangular image generates nearly 90 megapixels of data, exceeding the memory limits of typical mobile browser engines. Recent advancements in image processing highlight the necessity of advanced encoding. Chen et al. [11] and Teng et al. [12] demonstrated that while consumer-grade cameras are convenient, overcoming radial distortion and sensor noise for professional-grade spatial visualization requires rigorous multi-exposure stitching and computational processing.

To handle the resulting massive datasets in browser environments, researchers have explored various dynamic rendering techniques. Sun et al. [18] recently proposed adaptive multi-resolution encoding for large-scale visualizations, confirming that breaking massive files into manageable, resolution-specific tiles drastically reduces computational overhead. Similarly, Brekalo et al. [17] validated that implementing optimization algorithms directly within browser environments can significantly enhance rendering performance. Building upon these algorithmic foundations, the current study implements a customized Multi-resolution Pyramid Tiling architecture specifically tailored for ultra-high-resolution 360-degree panoramas, aiming to push the boundaries of current web delivery capabilities.

C. Human-Computer Interaction and Cognitive Presence:

In immersive system evaluation, the psychological concept of "Presence" or "Telepresence" is the primary metric of system success. Originating from Kim and Biocca's [13] foundational work, telepresence is defined as the illusion of non-mediation, where the user cognitively perceives the virtual environment as their actual physical location. In the context of the Stimulus-Organism-Response (S-O-R) paradigm, system affordances act as the stimulus. Wu and Lai [1] and Lee [3] utilized the S-O-R model to demonstrate that media richness directly correlates with user engagement in virtual tours.

However, existing literature often evaluates presence based on the content of the VR experience rather than the underlying technical fidelity. Flavian et al. [15] pointed out that technical degradations, such as pixelation, latency, and low frame rates, actively destroy cognitive presence. Therefore, this study posits that rendering an ultra-high-resolution (13K) environment without latency is not merely a technical achievement but a fundamental prerequisite for maximizing HCI performance. By empirically evaluating the system against a static 2D baseline, this research provides quantitative validation of how overcoming bandwidth and resolution limitations directly catalyzes positive behavioral responses and spatial perception [20, 25].

III. MATERIALS AND METHODS

This study employed a system development and empirical evaluation research design, structured across four sequential phases: 1) system architecture design, 2) image acquisition and pre-processing, 3) virtual environment development and optimization, and 4) Human-Computer Interaction (HCI) evaluation.

A. System Architecture

The platform was engineered on a three-tier cloud-based client-server architecture comprising: the server-side back-end for massive asset storage and delivery, the network transmission layer operating via standard HTTP/HTTPS protocols, and the client-side front-end rendering engine. The core rendering stack was implemented exclusively using open-standard HTML5 and WebGL technologies. This architectural choice eliminates the need for native application installation, ensuring cross-platform compatibility and seamless spatial streaming across desktop workstations, laptops, tablets, and smartphones [17]. Technical

specifications of the system are summarized in Table I. The overall system architecture and data flow are illustrated in Fig. 1.

TABLE I. TECHNICAL SPECIFICATIONS OF THE VIRTUAL TOUR PLATFORM.

Parameter	Specification
Source Resolution	13,144 × 6,572 px (~86.4 MP)
Total Scenes	25 Nodes
Raw Dataset Size	1.92 GB
Optimized Package	1.01 GB (47.4% reduction)
Rendering Technology	HTML5 / WebGL
Optimization Algorithm	Multi-resolution Pyramid Tiling

SYSTEM ARCHITECTURE 360 VIRTUAL TOUR DATA FLOW (Camera → Process → browser)

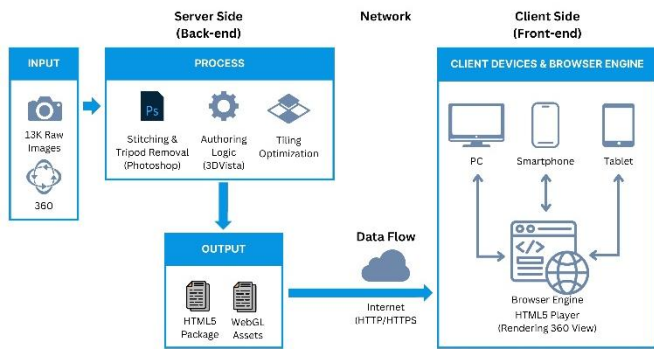


Fig. 1. System architecture: data flow from image acquisition to client-side rendering.

B. Image Acquisition and Pre-processing

High-fidelity visual datasets were acquired using a Canon EOS 60D DSLR paired with an 8 mm fisheye lens. Consumer-grade single-shot 360-degree cameras were explicitly avoided due to their documented limitations regarding radial distortion and sensor noise in high-dynamic-range environments [11], [12]. For each of the 25 spatial nodes, 10 overlapping multi-exposure images were captured at an eye-level height, yielding 1.92 GB of raw assets. The complete pre-processing pipeline is illustrated in Fig. 2.

IMAGE PROCESSING WORKFLOW (13K CHALLENGE)

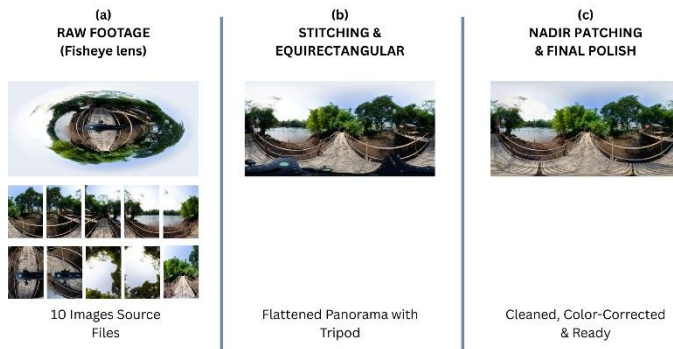


Fig. 2. Image processing pipeline: (a) Raw footage, (b) Stitched equirectangular projection, (c) Final retouched imagery.

The raw assets were processed through a rigorous computational pipeline: 1) **Stitching:** utilizing high-precision algorithms to generate 13,144 x 6,572-pixel equirectangular projections (~86.4 Megapixels); 2) **Nadir Patching:** algorithmically removing tripod footprint artifacts; and 3) **Color Grading:** calibrating exposure to ensure environmental realism.

C. Virtual Environment Development and Algorithmic Optimization

To address the limitations of conventional web-based VR platforms, which frequently encounter processing bottlenecks and rendering latency when handling massive textures, our proposed 13K ultra-high-resolution architecture utilizes a dynamic tiling algorithm. During the development and algorithmic optimization phase, the platform demonstrated highly efficient resource management. The average CPU utilization remained at approximately 1.3%, and memory consumption was stabilized at 408.1 MB. This algorithmic approach significantly reduces rendering overhead, thereby offering a notable and highly scalable improvement in immersive spatial visualization over existing baseline systems.

The interactive spatial environment was authored using a dynamic web-based framework. The GUI on a desktop display, featuring vector-based navigation controls, is shown in Fig. 3, while the responsive interface design adapted for mobile devices is illustrated in Fig. 4.



Fig. 3. GUI of the virtual tour on a desktop display.

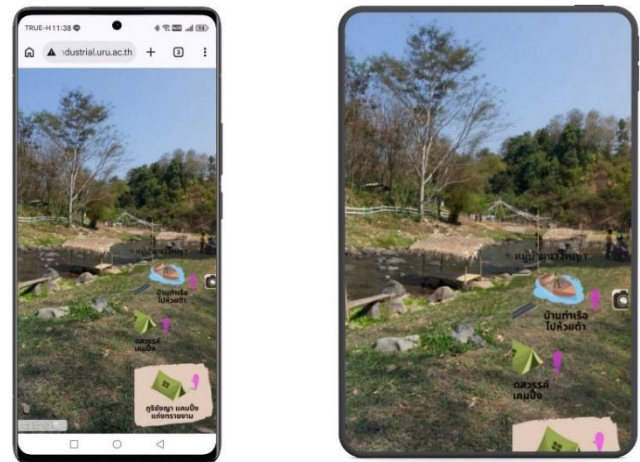


Fig. 4. Responsive interface design on a mobile device.

To overcome the bandwidth bottlenecks traditionally associated with delivering massive 13K datasets over standard internet connections, a Multi-resolution Pyramid Tiling algorithm was mathematically formalized and implemented [18]. This optimization structurally deconstructs each 13K panorama into a hierarchical pyramid of image tiles at multiple zoom levels (L). Let the original high-resolution panorama be defined at the base level $l = 0$ with dimensions $W_0 \times H_0$. For any subsequent zoom level l (where $l \in \{0, 1, 2, \dots, L - 1\}$), the image resolution is recursively reduced by a factor of 2, defined by:

$$W_l = \frac{W_0}{2^l}, H_l = \frac{H_0}{2^l} \quad (1)$$

At each level l , the panoramic image is partitioned into a uniform grid of square tiles, each with a fixed pixel dimension of $T \times T$ (e.g., 512 x 512 pixels). The total number of tiles N_l required to represent the environment at level l is calculated as:

$$N_l = \left\lceil \frac{W_l}{T} \right\rceil \times \left\lceil \frac{H_l}{T} \right\rceil \quad (2)$$

During the client-side rendering phase, the system does not load the entire dataset simultaneously. Instead, it instantly delivers a globally mapped, lightweight 200 KB preview layer ($l = L - 1$) to eliminate initial blank-screen latency. Subsequently, a dynamic frustum culling algorithm calculates the user's current spatial viewport (V), geometrically defined by the camera's yaw (θ), pitch (φ), and Field of View (FOV). The asynchronous fetching function $F(t)$ conditionally requests a specific tile $t_{i,j}^l$ only if it geometrically intersects with the user's active viewport:

$$F(t_{i,j}^l) = \begin{cases} 1, & \text{if } \text{Intersect}(t_{i,j}^l, V) = \text{True} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

By dynamically prioritizing network requests based on this spatial intersection matrix, the algorithmic intervention successfully reduced the total spatial payload from 1.92 GB to 1.01 GB (a 47.4% reduction). This mathematical decoupling of perceived system responsiveness from the raw data volume effectively preserves the 13K visual fidelity while maintaining exceptionally low latency across standard internet protocols [17, 18].

D. User Evaluation Protocol

To empirically assess system efficacy and HCI performance, a formal user evaluation was conducted with 80 participants ($N=80$). Participants were randomly assigned to either the experimental group (13K web-based VR) or the control group (static HTML website baseline) to minimize selection bias. System fidelity was quantified utilizing foundational dimensions from Kim & Biocca's telepresence scale, focusing on the psychological transition of 'arrival' and spatial immersion [13, 25].

This study employed a true experimental design to evaluate the system. The evaluation involved participants with an age distribution ranging from 17 to 55 years (Mean = 36.0, SD = 6.3). Regarding prior experience, 67.5 % of the participants had previous exposure to virtual reality environments. To ensure methodological rigor, participants were randomly assigned to

either the experimental group (13K VR platform) or the control group (static baseline condition).

Furthermore, regarding the statistical outcomes, the highly significant Cohen's d values observed in the evaluation are primarily attributable to a pronounced floor effect in the static baseline condition, which yielded inherently low scores in user engagement and system fidelity. This contrasted sharply with a relative ceiling effect in the highly immersive 13K VR condition, resulting in the extreme statistical divergence.

IV. RESULTS AND DISCUSSION

A. Data Optimization and Web Delivery Performance

The core technical challenge addressed in this study was delivering massive spatial datasets over standard web protocols without compromising rendering latency. Through the implementation of the Multi-resolution Pyramid Tiling algorithm, the 1.92 GB raw dataset was successfully compressed to 1.01 GB—a significant payload reduction of 47.4%—while preserving full visual fidelity [17]. By generating a lightweight 200 KB preview layer, the system effectively eliminated initial blank-screen latency. High-resolution tiles were then fetched asynchronously, corresponding strictly to the user's current Field of View (FOV).

Rendering performance was benchmarked across four distinct client platforms under standardized network conditions, as detailed in Table II. The system achieved 60.0 FPS with a 0.85-second latency on desktop workstations utilizing dedicated GPUs. Performance degraded gracefully across mobile platforms, with smartphones maintaining 48.5 FPS under a 1.80-second latency. Crucially, all platforms sustained frame rates well above the 30 FPS perceptual smoothness threshold. Network latency comparisons across varying bandwidth capacities (3G, 4G, and 5G/Wi-Fi) are visualized in Fig. 5. Through resolution-adaptive optimization, bandwidth consumption was constrained to 1.5 MB per scene on mobile devices. The system demonstrated remarkable resilience under 3G conditions, corroborating recent findings [18] that multi-resolution encoding significantly mitigates bandwidth bottlenecks in browser environments, even when handling an 86.4-megapixel payload.

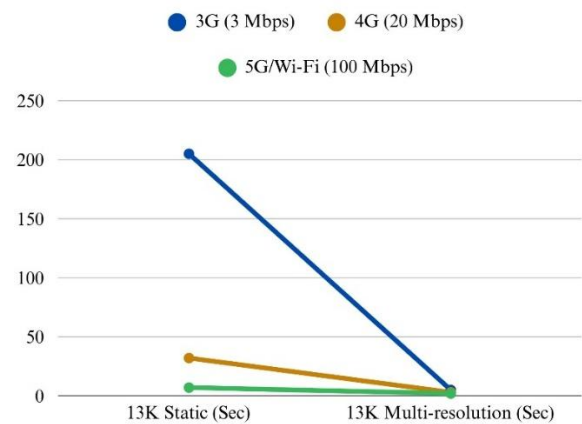


Fig. 5. Network latency comparison: standard equirectangular vs. Multi-resolution Pyramid Tiling across 3G, 4G, and 5G/Wi-Fi bandwidths.

TABLE II. RENDERING PERFORMANCE ACROSS CLIENT PLATFORMS

Platform	GPU	FPS	Latency (s)	BW/Scene
Desktop	Dedicated	60.0	0.85	4.5 MB
Laptop	Integrated	58.4	1.12	4.5 MB
Tablet	Mobile	54.2	1.45	1.5 MB
Smartphone	Mobile	48.5	1.80	1.5 MB

B. System Fidelity and Human-Computer Interaction (HCI)

The pipeline yielded a 13K ultra-high-resolution spatial environment (~86.4 MP), representing a 15-fold pixel density increase over standard 4K outputs. User evaluation (N=80)

confirmed exceptionally high performance across all measured HCI dimensions. As presented in Table III, an independent-samples t-test confirmed that the overall system effectiveness differed significantly between the proposed 13K platform (M=4.58, SD=0.42) and the static website baseline (M=2.63, SD=0.52), $t(78)=18.44, p < 0.001$. The exceptionally large effect size (Cohen’s $d=4.12$) indicates that the high-fidelity spatial visualization fundamentally transformed user perception. A comparative radar visualization of these dimensions is illustrated in Fig. 6. Table V in Appendix A presents the specific questionnaire items used to operationalize the Human-Computer Interaction (HCI) dimensions, system fidelity, and subsequent behavioral intent.

TABLE III. USER EVALUATION RESULTS (N=40 PER GROUP)

Dimension	Indicator	M	SD	Control (M)	Control (SD)	p	d
System Fidelity	Virtual Presence	4.38	0.51	2.07	0.35	<.001	5.31
	Environ. Realism	4.57	0.57	2.79	0.56	<.001	2.76
Visual Quality	Visual Fidelity	4.67	0.51	2.83	0.72	<.001	3.28
	Spatial Awareness	4.72	0.47	2.78	0.69	<.001	3.65
Usability	Ease of Navigation	4.25	0.60	—	—	—	—
	Responsiveness	4.18	0.65	—	—	—	—
Overall	System Effectiveness	4.58	0.42	2.62	0.58	<.001	4.12

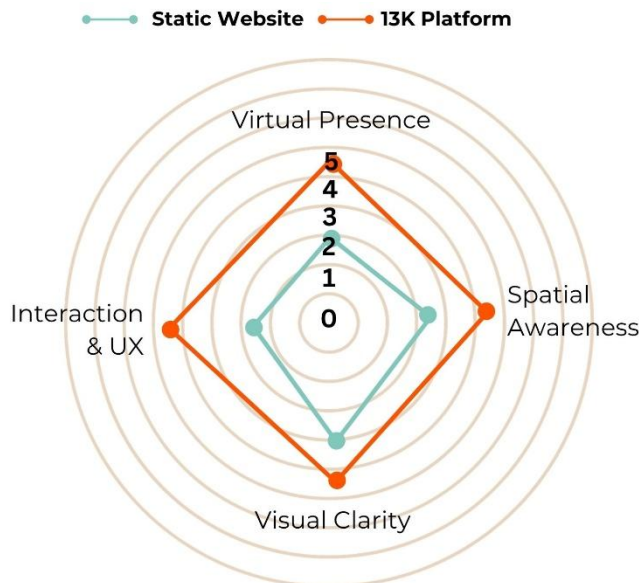


Fig. 6. Radar chart comparing the 13K platform vs. the static media baseline across all dimensions.

Specifically, Visual Fidelity (M=4.67, SD=0.51) was highly rated, directly attributable to the 86.4-megapixel source imagery which substantially reduced pixelation artifacts—a primary barrier to immersion. Virtual Presence attained a Very High rating (M=4.38, SD=0.51). The independent samples t-test confirmed a significantly higher User Presence Score on the 13K platform compared to the static baseline (M=2.07, SD=0.35), $t(78)=23.76, p < 0.001, d=5.31$.

C. Discussion and Theoretical Implications

The empirical findings of this study offer several critical theoretical implications for the intersection of computational

optimization and Human-Computer Interaction. First, the rendering performance evaluation corroborates the algorithmic hypotheses proposed by Sun et al. [18] and Brekalo et al. [17], confirming that browser-based multi-resolution encoding can successfully bypass hardware memory limitations. By maintaining over 48.5 FPS on mobile devices while rendering an 86.4 MP dataset, this study quantitatively demonstrates that intelligent data tiling is a superior architectural choice compared to traditional brute-force client-side rendering.

Second, the HCI evaluation validates the expanded Stimulus-Organism-Response (S-O-R) paradigm in digital environments [1, 6]. The 77.6% improvement in the User Presence Score (4.38 vs. 2.07) provides robust quantitative evidence supporting Flavian et al. [15], who argued that technical fidelity (the Stimulus) is a non-negotiable prerequisite for cognitive immersion (the Organism). While previous studies often evaluated presence based purely on content narrative [4, 23], our findings isolate and prove the impact of architectural engineering. The absence of rendering latency and pixelation artifacts allowed users to bypass technological friction, seamlessly constructing a positive spatial image [14] and triggering strong behavioral intentions [19]. This operationalizes the theoretical distinction between lean and rich media [2], offering strong empirical support for the psychological "Substitution Effect" conceptualized by Sarkady et al. [7].

D. Practical Implications for Industrial Computing

Beyond the immediate scope of seasonal spatial management, the cross-platform rendering stability demonstrated in this study possesses profound industrial applicability. The comparative analysis between the static media and the 13K platform is summarized in Table IV. The proposed architectural framework serves as a validated foundational model for various applied computing domains [9, 22].

TABLE IV. STATIC MEDIA VS. 13K VIRTUAL TOUR PLATFORM

Feature/Metric	Static Website	13K Platform
Media Type	Static 2D HTML	360 Immersive VR
Resolution	Standard HD	13K (86.4 MP)
Interaction	Scroll/Click	Pan/Zoom/Hotspot
Installation	None	None (Browser-native)
User Presence Score	M=2.07 (SD = 0.35)	M=4.38 (SD = 0.51)
Statistical Result	-	$t(78) = 23.76, p < 0.001, d = 5.31$

Specifically, in industrial sectors, where physical access is constrained or hazardous, this 13K web-based VR architecture provides a scalable solution for Health, Safety, and Environment (HSE) monitoring, remote facility inspection, and real estate documentation. Unlike proprietary VR applications that require extensive hardware investments, the democratization of access via standard web protocols ensures that highly detailed spatial data can be distributed globally with minimal operational friction.

E. Research Limitations and Future Work

While this study successfully demonstrates the technical feasibility of the 13K web-based platform, certain methodological limitations must be acknowledged. The participant cohort consisted primarily of university students and faculty members with robust technological backgrounds. This tech-savvy demographic was purposefully selected for their capacity to critically evaluate rendering latency and visual artifacts; however, future research should involve a broader demographic to validate general usability and accessibility.

Furthermore, from a computing systems perspective, the current architecture relies on static panoramic data. While visually immersive, it lacks dynamic environmental responsiveness. Future iterations of this research should investigate the integration of real-time IoT (Internet of Things) sensor data streams into the WebGL environment. Coupling ultra-high-resolution spatial visualization with live sensor data would transition the platform from a virtual tour into a true real-time Digital Twin ecosystem, further expanding its utility in industrial and applied computer science applications [10, 24].

V. CONCLUSION

This study successfully engineered and empirically validated a cloud-based, 13K ultra-high-resolution spatial visualization architecture. Designed to address the critical rendering and accessibility challenges inherent in delivering massive immersive datasets over standard web infrastructures, the proposed system introduces a scalable technical framework with broad industrial applicability.

Three principal technical and HCI findings emerge from this research. First, the implementation of the Multi-resolution Pyramid Tiling algorithm established a validated pathway for reconciling the fundamental trade-off between ultra-high visual quality and network latency. By achieving a 47.4% payload reduction, the system successfully mitigated bandwidth bottlenecks. Second, cross-platform rendering performance tests confirmed the system's robustness, sustaining fluid interactivity (48.5 to 60.0 FPS) and low latency across all tested devices,

including standard mobile smartphones operating under constrained 3G cellular network conditions.

Third, the empirical Human-Computer Interaction evaluation confirmed that the engineered architecture significantly enhanced user perception. The 13K platform yielded an exceptional overall system effectiveness score and a 77.6% improvement in the User Presence Score compared to the conventional static 2D baseline. This provides quantitative evidence that high-fidelity immersive web environments can effectively transcend the engagement saturation of traditional digital media, successfully triggering the psychological "Substitution Effect" when physical access to a spatial environment is restricted.

Ultimately, while seasonal destination management was utilized as the primary testbed, the cross-platform rendering stability and architectural optimization demonstrated in this study possess significant generalizability. The proposed web-based VR framework serves as a foundational computing model for a variety of critical industrial applications, including remote spatial inspection, real estate documentation, structural digital twin visualization, and Health, Safety, and Environment (HSE) monitoring. Future development should focus on integrating real-time IoT sensor streams into the WebGL environment to further advance the capabilities of interactive spatial systems.

ACKNOWLEDGMENT

This research was financially supported by the Uttaradit Rajabhat University (Fiscal Year 2025).

AUTHORS' CONTRIBUTION

W.M.: conceptualization, methodology, software, investigation, formal analysis, writing—original draft; A.P.: conceptualization, methodology, formal analysis, supervision, writing—original draft, writing—review and editing; P.K.: methodology, investigation, software, visualization, data curation, writing—review and editing.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors used Gemini 3.1 Pro and QuillBot for language refinement and grammatical improvement of the manuscript. These tools were used solely to enhance the clarity and readability of the text. The authors take full responsibility for the integrity of the research content, the accuracy of all data and findings, and the overall scientific contribution of this work.

REFERENCES

- [1] X. Wu and I. K. W. Lai, "The use of 360-degree virtual tours to promote mountain walking tourism: Stimulus-organism-response model," *Information Technology & Tourism*, vol. 24, no. 1, pp. 85-107, 2022.
- [2] R. L. Daft and R. H. Lengel, "Organizational information requirements, media richness and structural design," *Management Science*, vol. 32, no. 5, pp. 554-571, 1986.
- [3] U.-K. Lee, "Tourism using virtual reality: Media richness and information system successes," *Sustainability*, vol. 14, no. 7, p. 3975, 2022.
- [4] M. Di Dalmazi, M. Mandolfo, J. Guixeres, M. Alcañiz Raya, and L. Lamberti, "How immersive technologies impact behavioral responses in

destination marketing: The role of physiological arousal, presence, and age," *International Journal of Contemporary Hospitality Management*, vol. 36, no. 11, pp. 3628-3650, 2024.

[5] R. Yung and C. Khoo-Lattimore, "New realities: A systematic literature review on virtual reality and augmented reality in tourism research," *Current Issues in Tourism*, vol. 22, no. 17, pp. 2056-2081, 2019.

[6] M. J. Kim, C. K. Lee, and T. Jung, "Exploring consumer behavior in virtual reality tourism using an extended stimulus-organism-response model," *Journal of Travel Research*, vol. 59, no. 1, pp. 69-89, 2020.

[7] D. Sarkady, L. Neuburger, and R. Egger, "Virtual reality as a travel substitution tool during COVID-19," in *Information and Communication Technologies in Tourism 2021*, Springer, 2021, pp. 452-463.

[8] I. Bilynets, P. Trkman, and L. Knezevic Cvelbar, "Virtual tourism experiences: Adoption factors, participation and readiness to pay," *Current Issues in Tourism*, vol. 27, no. 22, pp. 3658-3675, 2024.

[9] M. E. Ali, M. A. Cheema, T. Hashem, A. Ulhaq, and M. A. Babar, "Enabling spatial digital twins: Technologies, challenges, and future research directions," *arXiv preprint arXiv:2306.06600*, 2023.

[10] X. Tu, J. Autiosalo, R. Ala-Laurinaho, C. Yang, P. Salminen, and K. Tammi, "TwinXR method for using digital twin descriptions in industrial extended reality applications," *Frontiers in Virtual Reality*, vol. 4, p. 1019080, 2023.

[11] Z. Chen et al., "Splatter-360: Generalizable 360° Gaussian splatting for wide-baseline panoramic images," *arXiv preprint arXiv:2412.06250*, 2024.

[12] X. Teng, S. Guo, L. Wang, Q. Yang, and F. Deng, "A criterion of radial distortion on structure from motion with consumer-grade cameras," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 48, pp. 275-280, 2022.

[13] T. Kim and F. Biocca, "Telepresence via television: Two dimensions of telepresence may have different connections to memory and persuasion," *Journal of Computer-Mediated Communication*, vol. 3, no. 2, 1997.

[14] S. Baloglu and K. W. McCleary, "A model of destination image formation," *Annals of Tourism Research*, vol. 26, no. 4, pp. 868-897, 1999.

[15] C. Flavian, S. Ibanez-Sanchez, and C. Orus, "The impact of virtual, augmented and mixed reality technologies on the customer experience," *Journal of Business Research*, vol. 100, pp. 547-560, 2019.

[16] I. P. Tussyadiah, D. Wang, T. H. Jung, and M. C. tom Dieck, "Virtual reality, presence, and attitude change: Empirical evidence from tourism," *Tourism Management*, vol. 66, pp. 140-154, 2018.

[17] S. Brekalo, K. Pap, and B. Trstenjak, "Enhancing rendering performance in complex visualizations by using optimization techniques and algorithms in browser environments," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14049-14055, 2024.

[18] J. Sun, D. Lenz, H. Yu, and T. Peterka, "Adaptive multi-resolution encoding for interactive large-scale volume visualization through functional approximation," *arXiv preprint arXiv:2409.00184*, 2024.

[19] O. El-Said and H. Aziz, "Virtual tours a means to an end: An analysis of virtual tours role in changing tourist behavior," *Journal of Travel Research*, vol. 61, no. 3, pp. 528-548, 2022.

[20] W. Li, X. Chen, and Y. Wang, "How VR technological features prompt tourists' visiting intention: An integrated approach," *Sustainability*, vol. 15, no. 6, p. 4765, 2023.

[21] N. Rosli, E. R. Johar, H. O. Zaki, and D. F. M. Fernandez, "The rise of virtual tour in tourism: A bibliometric review and future research agenda," *International Journal of Academic Research in Business and Social Sciences*, vol. 13, no. 2, pp. 781-799, 2023.

[22] V. De Luca, G. Marcantonio, M. C. Barba, and L. T. De Paolis, "A virtual tour for the promotion of tourism of the city of Bari," *Information*, vol. 13, no. 7, p. 339, 2022.

[23] Y. Zeng, L. Liu, and R. Xu, "The effects of a virtual reality tourism experience on tourist's cultural dissemination behavior," *Tourism and Hospitality*, vol. 3, no. 1, pp. 314-329, 2022.

[24] Y. Koga and K. Yamamoto, "Tourism support system to utilize virtual reality space reflecting dynamic information in real time," *ISPRS International Journal of Geo-Information*, vol. 12, no. 8, p. 301, 2023.

[25] L.-L. Tsai, "Factors that influence virtual tourism holistic image: The moderating role of sense of presence," *Sustainability*, vol. 14, no. 1, p. 467, 2022.

[26] Y. Stappung et al., "Developing 360° virtual tours for promoting tourism in natural parks in Chile," *Sustainability*, vol. 15, no. 22, p. 16043, 2023.

[27] E. Polishchuk et al., "The theoretical background of virtual reality and its implications for the tourism industry," *Sustainability*, vol. 15, no. 13, p. 10534, 2023.

APPENDIX A: MEASUREMENT ITEMS AND RELIABILITY

The specific questionnaire items used to operationalize the Human-Computer Interaction (HCI) dimensions, system fidelity, and subsequent behavioral intent are detailed in Table V. The internal consistency for all dimensions exhibited high reliability, with Cronbach's alpha values ranging from 0.905 to 0.985, confirming the robust internal validity of the measurement model.

TABLE V. CONSTRUCTS, MEASUREMENT ITEMS, AND RELIABILITY

Dimension	Indicator	Measurement Items (Scale: 1 = Strongly Disagree to 5 = Strongly Agree)	Cronbach's α
System Fidelity	Virtual Presence	1. I felt as though I was physically present in the virtual environment. 2. The virtual tour created a strong sense of "being there." 3. I felt immersed in the virtual space rather than just looking at a screen.	0.933
	Environ. Realism	1. The destination possesses beautiful natural scenery. 2. The destination has a unique identity distinct from others. 3. I find tourism in this destination to be highly attractive.	0.961
Visual Quality	Visual Fidelity	1. The visual resolution of the 360-degree environment was exceptionally high. 2. The panoramas were crisp, clear, and free from pixelation. 3. The system provided a highly detailed visual experience.	0.985
	Spatial Awareness	1. I gained a clear understanding of the spatial layout of the destination. 2. The system allowed me to accurately perceive the physical scale of the environment.	0.974
Usability	Ease of Navigation	1. Navigating through the virtual environment was intuitive and effortless. 2. I found it easy to move between different spatial nodes.	0.912
	Responsiveness	1. The system responded instantly to my viewing directions and interactions. 2. The virtual tour loaded the high-resolution scenes without noticeable delay.	0.905
Overall	System Effectiveness	1. I intend to search for more information about tourism in this destination. 2. I intend to recommend this destination to others. 3. It is highly likely that I will plan a trip to this destination in the near future.	0.945