A 3D GIS Perspective Towards the Occlusion Problem in XR Environment

Chang, H.H.[1],* and Hong, J.H.[2]

[1] Institute of Geomatics, National Cheng Kung University, Tainan, Taiwan

[2] Professor of Institute of Geomatics, National Cheng Kung University, Tainan, Taiwan

*p66134072@gs.ncku.edu.tw

Abstract **:** *Extended Reality (XR) represents the convergence of physical and virtual environments, thereby creating a new operational framework. Within this context, Virtual Reality (VR) and Augmented Reality (AR) offer unique perspectives that enable innovative applications. VR is primarily concerned with delivering a fully immersive experience within a completely virtual setting, whereas AR focuses on the concurrent presentation of virtual elements alongside the physical world. A significant challenge encountered in XR environments is the "occlusion problem," which negatively impacts spatial realism and depth perception when users engage with the virtual environment. The challenges associated with VR and AR applications, however, differ considerably. VR applications prioritize the completeness of phenomena and the accuracy of spatial representation, while AR applications must also account for the spatial relationships between virtual information, real-world objects, and users. Inadequate management of occlusion can result in the erroneous rendering of virtual information in front of real objects. This research aims to investigate the occlusion problem within XR environments by employing 3D Geographic Information System (GIS) data as a reference for constructing models in the virtual domain. By harnessing the benefits of multi-dimensional spatial representation and precise positioning, along with rendering techniques from computer graphics, the study aspires to establish an accurate visual relationship between occluders and occluded objects. The investigation begins with an analysis of observable phenomena from the user's perspective, contrasting the considerations necessary for the distinct development of VR and AR simulated environments, and proposes strategies to alleviate the occlusion problem through the inclusion of 3D GIS data. A campus environment has been selected as a practical case study, which includes a web-based interactive platform that integrates XR technology. This initiative not only demonstrates the efficacy of system integration and application but also explores its potential advantages and the challenges related to practical implementation.*

Keywords: Extended Reality, Virtual Reality, Augmented Reality, Geographic Information Systems, Occlusion Problem

Introduction

With the continuous advancement of sensors and survey technologies, a large volume of environmental data has been systematically collected in three-dimensional Geographic Information Systems (3D GIS). At the same time, the advent of the digital era has facilitated the constant circulation of multi-source, cross-domain real-time data. How to effectively link virtual data with the real environment has become a critical issue that the field of geomatics urgently needs to address. Extended Reality (XR) is a collective term for technologies that integrate real and virtual environments, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) (Doolani et al., 2020). VR refers to a fully computer-generated 3D virtual space, wherein the virtual world responds in real time to user movements or interactions, thereby creating an immersive and realistic experience. AR emphasizes the interaction among users, digital content, and the real world, enabling virtual images to be overlaid onto visual scenes while maintaining the perspective of the real environment (Xiong et al., 2021). MR represents the fusion of AR and VR, highlighting the combination of virtual and real environments; it goes beyond merely "seeing" virtual object overlays, as in AR, and enables interaction with and manipulation of virtual worlds or objects in the real world through various sensor technologies (e.g., touchscreens, IMUs, GPS), AI-based image recognition, or real-time environmental sensing data (Chai et al., 2022). Within this developmental context, numerous companies have actively launched proprietary devices and brands. For instance, Microsoft introduced its mixed reality device, the HoloLens; Meta acquired the VR company Oculus as part of its transformation into a "metaverse" enterprise (Rauschnabel et al., 2022); and Apple released the Apple Vision Pro, which enables users to interact AR virtual objects in a natural and intuitive manner.

In terms of practical applications, one of the most successful recent VR applications has been Digital Twin. By constructing highly realistic virtual environments and continuously integrating real-time data, Digital Twin can accurately simulate the behavior of physical systems within virtual environments. Through this mechanism of virtual–real synchronization, it provides not only a method for scenario simulation and prediction but also supports the formulation of optimization strategies and best solutions, while enabling continuous monitoring and evaluation of system operational states (Semeraro et al., 2021). This technology has been widely applied in smart manufacturing (Tao et al., 2019), smart cities (Ham & Kim, 2020), smart healthcare (Liu et al., 2019) , and urban digital twins (Ferré-Bigorra et al., 2022). Regarding AR applications, beyond the early representative cases such as the game Pokémon GO (Rauschnabel et al., 2017) and Google Glass (which presented maps, images, and video calls in an augmented manner) (Parida et al., 2021), AR has recently begun to demonstrate its potential and feasibility across multiple domains, including manufacturing (Ong et al., 2008), healthcare (Vavra et al., 2017), and education (Fuchsová et al., 2020).

However, advancing VR and AR toward MR to achieve "fusion of the virtual and the real" is not a trivial task, with the occlusion problem representing a critical challenge that directly affects users' perception of visual realism in XR experiences. The occlusion problem can be understood as the emergence of erroneous visual relationships within XR environments. For instance, in VR applications, when visual relationships fail to accurately reflect those of the real world, incorrect occlusion relationships arise between virtual objects and the virtual environment. Furthermore, in the context of Digital Twin applications, the Digital Twin concept emphasizes the mapping of virtual environments to the real world, which is fundamentally composed of three elements: physical entities, virtual models, and twin data (Liu et al., 2023). Among these, the virtual models are the core key that distinguishes digital twin technology from other technologies, and is also the foundation for realizing interaction between the virtual and real worlds (Tao et al., 2022). Therefore, the fidelity of the virtual model within the virtual environment directly influences the spatial positioning and visual occlusion relationships in VR, thereby exerting a consequential impact on subsequent decision-making processes. On the other hand, in AR applications, beyond ensuring precise alignment between virtual and real objects, the occlusion problem remains a central challenge that directly impacts user experience. Most AR applications, due to the lack of depth information from the real environment, merely overlay virtual objects onto the camera view. This approach frequently results in virtual objects being erroneously rendered in front of real objects (e.g., in Figure 1 (a), when attempting to render a virtual object behind a wall, without occlusion handling, the result will appear as shown in Figure 1 (b)). Such incorrect occlusion relationships can lead to confusion in users' depth perception (Zhu et al., 2009) and are therefore unsuitable for complex application scenarios.

(a) (b)

Figure 1: The AR occlusion problem.

Based on the challenges outlined above, this study first examines user needs and observable phenomena from the users' perspective, followed by a comparison of the technical considerations necessary for constructing VR and AR environments from the developer's standpoint. Building on this analysis, the study proposes a strategy that combines existing 3D GIS data with computer graphics rendering techniques to achieve more accurate visual relationships between occluders and occluded objects. Finally, this study uses a campus environment as a case study and, based on the proposed strategy, employs self-constructed virtual models combined with web development and XR technologies to build a VR and AR application scenario simulating the installation of solar panels on departmental building rooftops. The system provides an interactive platform accessible to the general public via a web browser, thereby concretely demonstrating the feasibility and practical benefits of the proposed approach.

Literature Review

VR and AR possess excellent capabilities for visualizing virtual data, whereas 3D GIS provides extensive geospatial data and robust data processing capabilities. The integration of these two technologies can yield a more interactive experiential framework. As noted by Pavelka and Landa (Pavelka & Landa, 2024) established a workflow for VR and AR visualization of GIS data, in which geospatial data were processed in QGIS and exported as 3D models. These models were then rendered using a game engine to display traditional GIS data through VR and AR technologies, while providing basic interactive functionalities such as layer switching, layer blending, and temporal change visualization. Furthermore, Safari Bazargani et al. (Safari Bazargani et al., 2022) proposed that AR can serve as a bridge between 2D and 3D visualization by simultaneously presenting real and virtual geospatial information, thereby creating a more interactive experience that can address the limitations of GIS in intuitive perception and reduce the difficulties users may encounter when interpreting spatial information. At the same time, GIS provides capabilities for storing, processing, and analyzing geospatial data, thereby compensating for AR's constraints in data management and analysis. Furthermore, the study categorizes the integration of AR and GIS into three specific application types: AR Mapping, which presents information through visualization and mapping; AR Analysis, which utilizes AR for data collection and measurement and integrates these into GIS; and AR Positioning, which encompasses both indoor and outdoor positioning. These three categories enable a comprehensive examination of the potential benefits arising from the integration of AR and GIS across different domains.

However, to achieve true "fusion of the virtual and the real," mere integration of 3D GIS data is insufficient; it is necessary to further address the occlusion problem. For instance, del Campo et al. (del Campo et al., 2024) employed GPS coordinate data to precisely position detailed urban elements and their associated sensor models within a VR virtual scene, and further incorporated high-resolution imagery as model textures to enhance visual realism. Through this process, a correct and comprehensive visual occlusion relationship was established, ensuring that the spatial interplay between objects in the virtual environment accurately reflects that of the real world. In the context of AR applications, addressing the occlusion problem requires first establishing the relative spatial relationships among virtual objects, physical entities, and users, followed by detecting the regions of real-world objects that may occlude virtual content. Existing approaches can be broadly categorized into three types: depth-based (Li et al., 2022; Tian et al., 2015), AI-based (Ogawa & Mashita, 2021; Tian et al., 2021) , and model-based (Alfakhori et al., 2023; Kikuchi et al., 2022) methods. The depth-based methods primarily rely on hardware devices to directly acquire environmental depth information, such as stereo cameras, Time-of-Flight (ToF) cameras, and LiDAR sensor. These methods are constrained by hardware limitations, and due to restricted measurement ranges (e.g., the LiDAR built into the iPhone 15 Pro has a maximum range of approximately 5 meters) and susceptibility to environmental interference, they are difficult to apply extensively in large-scale outdoor scenarios. The AI-based methods estimate depth or occlusion from RGB images using artificial intelligence. As shown by Ogawa and Mashita (2021) , combining image segmentation with map data can compensate for inaccuracies in GPS positioning. However, the effectiveness of this method is highly dependent on the AI training model and the quality of the training data, while the training outcomes are subject to instability and latency. In other words, this approach struggles to ensure consistency in occlusion handling, and the need to perform recognition on every single frame further constrains the real-time performance of occlusion processing. The model-based methods rely on pre-established 3D virtual models of the real environment. During preprocessing, target models and occlusion models are constructed within the virtual scene and aligned with the real-world environment; occlusion handling is then performed by comparing the depths of the virtual 3D models and occlusion models. For example, Alfakhori et al. (2023) employed LOD1 and 3D mesh models in combination with tracking techniques to achieve occlusion handling in both indoor and outdoor environments. The advantage of this approach lies in its reliance solely on the precise environmental data provided by 3D GIS and the environment models derived therefrom. By integrating users' real-time position and orientation information, it can accurately determine the correct visual relationships between occluding and occluded objects.

Methodology

This section is organized into four perspectives: User's perspective, Developer's perspective, 3D GIS, and Computer Graphics Rendering. The User and Developer perspectives provide distinct viewpoints to examine usage requirements and technical demands, and to analyze the differences between VR and AR in detail, thereby offering a foundation for subsequent practical case development and technical reference. From the 3D GIS and computer graphics rendering perspectives, the discussion focuses on how these technologies are employed to propose technical strategies and solutions for addressing the occlusion problem in VR and AR applications.

a. User' perspective

From the user's standpoint, both VR and AR provide highly interactive experiences. However, significant differences remain between the two in terms of applications, data requirements and user interfaces.

Regarding applications, VR is characterized by its ability to create fully immersive virtual environments, enabling scenarios unattainable in the real world, such as instantaneous teleportation, multi-perspective switching, and the simulation of extreme or complex situations. Consequently, VR has been widely applied in domains such as gaming and entertainment, disaster simulation, environmental monitoring, and urban digital twins. Beyond immersive experiences, VR also supports real-time decision-making and facilitates urban planning and management. By contrast, AR is distinguished by its capacity to superimpose virtual information directly onto the real world, making it particularly suitable for contexts requiring real-time, on-site informational support, such as navigation, maintenance operations, or field data collection and simulation. Furthermore, AR applications can be classified according to their mobility and operational environments into five categories: fixed indoor systems, fixed outdoor systems, mobile indoor systems, mobile outdoor systems, and mobile indoor–outdoor systems (Carmigniani et al., 2010) , each with distinct developmental considerations and equipment constraints.

In terms of data requirements, VR must rely on accurate and comprehensive environmental data to faithfully simulate real-world scenarios within virtual environments, while also integrating information tailored to user-specific needs. For instance, environmental monitoring requires the incorporation of real-time sensor data, whereas urban digital twins demand the continuous integration of traffic flow data. In contrast, AR benefits from the direct presence of the real world as contextual support and thus does not require the inclusion of all available data. Instead, AR emphasizes the integration of only critical information, particularly that which does not exist in reality or cannot be directly observed. Moreover, numerous studies (Jones et al., 2020; Lu et al., 2020) have highlighted the pivotal role of the Internet of Things (IoT) in enabling XR applications. By facilitating the continuous transmission of real-time data, IoT allows both VR and AR to support real-time monitoring, simulation, and analysis, thereby deepening the understanding of complex urban systems and promoting data-driven decision-making and adaptive strategies.

With respect to the user interface, the design of VR emphasizes leveraging the advantages of fully virtual environments by presenting information in a comprehensive and immersive manner. This is often achieved through diverse functional interfaces, such as virtual information panels, interactive buttons, and 3D objects, enabling users to intuitively manipulate and explore virtual scenes. In contrast, AR interface design must balance the presentation of both virtual information and real-world contexts, placing emphasis on clarity and immediacy of information. To avoid excessive interference with the real-world view, AR systems often filter out redundant or irrelevant elements from the real-world or employ toggles to regulate the display of virtual content. Such approaches ensure visual clarity and user focus, while simultaneously enhancing interaction efficiency and situational understanding.

Table 1: Comparison of VR and AR from the user's perspective.

Aspect	VR	AR
Application	Provides a fully virtual, immersive environment, enabling scenarios unattainable in the real world. Widely applied in gaming, disaster simulation, environmental monitoring, and urban digital twins, offering immersive experiences, supporting real-time	Superimposes virtual information onto the physical world, delivering real-time, on-site support. Common applications include navigation, maintenance operations, field data collection, and simulation, enhancing situational awareness and decision-making.

	decision-making, and facilitating urban planning and management.	Depending on mobility and environmental context, AR applications can be categorized into five types: fixed indoor, fixed outdoor, mobile indoor, mobile outdoor, and mobile indoor–outdoor.
Data Requirement	To accurately simulate real-world contexts, VR requires precise and comprehensive environmental data, supplemented by application-specific datasets. Real-time data play a pivotal role in enabling monitoring, simulation, and analysis.	Based on the real world, it is not necessary to incorporate all data; instead, the focus is on supplementing key information that is either absent or difficult to directly observe. Real-time data play a pivotal role in enabling monitoring, simulation, and analysis.
User Interface	Emphasizes the immersive presentation of virtual information, providing diverse interfaces—such as virtual panels, interactive buttons, and 3D objects—that allow users to intuitively manipulate and explore virtual scenes.	Displays virtual content alongside the physical environment, prioritizing intuitiveness and immediacy. Redundant information is filtered or managed via toggles to prevent interference with the real-world view, ensuring clarity, focus, and enhancing interaction efficiency and situational understanding.

b. Developer's perspective

To advance the development of XR technologies, this study examines VR and AR across three aspects: hardware, software, and data processing.

At the data level, the realization of XR technology fundamentally depends on the real-time rendering of 3D scenes. As data volumes continue to increase, the computational demands for 3D scenes grow exponentially. This challenge is particularly pronounced in VR, where constructing large-scale virtual worlds requires high-performance Graphics Processing Units (GPUs) as the key devices to ensure smoothness and low latency in immersive experiences. By contrast, although the graphical computational load in AR is relatively lower, its core challenge lies in real-time environmental perception and high-precision positioning. Consequently, when user have mobile needs, AR systems typically integrate diverse localization and ranging sensors, including LiDAR, stereo cameras, GPS, and UWB (Ultra-Wideband). However, AR places particularly high demands on sensing precision, which makes it essential to account for the distinct conditions of indoor and outdoor environments. For instance, GPS is insufficiently precise in indoor settings, while LiDAR and stereo cameras in outdoor contexts must overcome limitations such as measurement range, variations in lighting, and interference from occluding objects.

At the software level, GIS platforms (e.g., QGIS, ArcGIS) provide the capability to process spatial data, while 3D modeling tools (e.g., Blender, SketchUp) enable the construction of high-precision digital twin models, which constitute the core virtual models within XR systems. Moreover, since VR applications frequently involve rendering large-scale 3D environments, they additionally rely on rendering engines or game engines (e.g., Unity, Unreal Engine, Godot Engine) as essential tools for development and deployment. In contrast, AR systems, beyond these aforementioned tools, require the integration of cameras and multiple sensors. Therefore, during development, AR applications are often accompanied by dedicated AR Software Development Kits (SDKs), such as ARKit for iOS or ARCore for Android, in order to ensure real-time consistency in localization, tracking, and rendering functions.

At the data processing level, creating highly realistic virtual scenes in VR environments requires not only complete and high-precision 3D geographic information and environmental models, but also careful consideration of differences in coordinate reference systems between the real and virtual worlds. For example, the real world typically uses latitude, longitude, and altitude as positional coordinates, whereas virtual environments commonly adopt an XYZ coordinate system or may differ in scale from reality. Consequently, 3D geographic data cannot be directly applied to virtual environments and must be transformed via a conversion matrix that maps real-world coordinates and pose information into the virtual world’s coordinate system. For AR environments, ensuring that virtual objects accurately align with real-world scenes requires the integration of high-precision 3D geographic information along with multi-source sensor data from cameras, positioning systems, and measurement devices, thereby guaranteeing correct object placement, computation, and rendering. Furthermore, in both VR and AR applications, diverse datasets must be integrated according to user requirements. Real-time sensor data can be interfaced via IoT systems and, after appropriate filtering based on user context, status, and location, can be dynamically or statically reflected in the virtual objects.

Table 2: Comparison of VR and AR from the developer's perspective.

Aspect	VR	AR
Hardware	Relies on high-performance GPUs to support real-time rendering of large-scale 3D scenes, ensuring smoothness and low latency in immersive experiences.	Graphical computation load is lower but requires real-time environmental perception and high-precision positioning; integrates diverse sensors (LiDAR, stereo cameras, GPS, UWB), with consideration of differences between indoor and outdoor environments.
Software	Depends on GIS platforms (e.g., QGIS, ArcGIS) for spatial data processing, and 3D modeling tools (e.g., Blender, SketchUp) for constructing digital twin models; rendering and deployment rely on game engines (e.g., Unity, Unreal Engine, Godot Engine).	In addition to GIS and modeling tools, AR must also support integration of cameras and multiple sensors; development commonly employs AR-specific SDKs (e.g., ARKit, ARCore) to ensure real-time consistency in localization, tracking, and rendering.
Data	Must account for differences between real-world and virtual-world coordinate systems, using transformation matrices to map coordinates; integrates multi-source and IoT data according to user requirements, with appropriate filtering to dynamically or statically reflect information in the virtual environment.	Integrates high-precision 3D geographic information with multi-source sensor data from cameras, positioning, and measurement devices to ensure correct object placement, computation, and rendering; also incorporates multi-source and IoT data according to user requirements, with appropriate filtering to dynamically or statically reflect information in the virtual environment.

c. 3D GIS

In XR applications, virtual models serve as the foundation for enabling interactions between the virtual and real worlds. If these models fail to accurately reflect the state of virtual objects within the real environment, they not only undermine the user's sense of realism but may also introduce unpredictable consequences for subsequent decision-making. Therefore, the ability of a virtual model to faithfully reproduce the structure, dimensions, properties, and spatial position of real-world objects with high precision is a key determinant of the effectiveness of this technology. Within this framework, 3D GIS provides the comprehensive and indispensable twin data support. Not only does 3D GIS encompass rich and complete spatial datasets, but it also offers robust capabilities for data processing and filtering. Through the integration of diverse environmental datasets and modeling software, high-precision and comprehensive environmental models can be constructed. Furthermore, by combining the spatial and attribute information supplied by 3D GIS with the established environmental models and real-time environmental data, the implementation of VR-based Digital Twin applications becomes feasible. Building upon this foundation, if the environmental model is further integrated with the user's current position and orientation information, it can be extended to fundamental AR applications. Moreover, through model-based approaches in occlusion handling, the spatial relationships between occluders and occluded objects can be precisely determined, and ultimately, computer graphics rendering techniques can realize correct visual relationships of virtual objects within the real world.

d. Computer graphics rendering

In AR applications, to ensure that virtual objects exhibit correct visual relationships with real-world entities, the environment models previously constructed using 3D GIS and modeling software must be treated as occluders. Based on these models, a model-based approach is employed to identify regions of real objects that would occlude virtual objects, and the corresponding occluded pixels of the virtual objects are discarded. This process relies on the principle of the *z-test* in computer graphics rendering (Alfakhori et al., 2023). Computer graphics can be conceptualized as a series of processes that generate 2D and 3D images and output them to the user's display device, comprising three main stages: vertex processing, rasterization, and fragment processing. The z-test is part of the fragment processing stage. Here, "z" represents the depth coordinate of a pixel, indicating the virtual object's position relative to the observer; thus, the z-test is also referred to as depth testing. During this process, the depth value (z value) of each pixel of a virtual object is evaluated. If a pixel is detected to be located behind another pixel (i.e., its z value is greater than that of a front-facing pixel), it is discarded. Only pixels that pass the z-test are written into the depth buffer, thereby preventing implausible overlapping in the rendered scene.

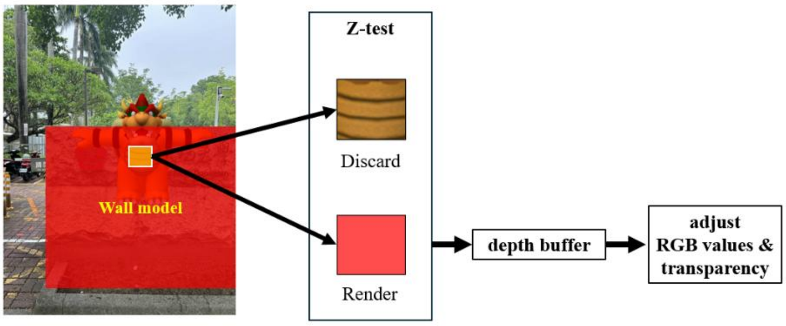


Figure 2: Flowchart of the z-test

Through this rendering mechanism, when all virtual objects—including occluders and occluded objects—are rendered into the scene with depth testing enabled, and the occluders are assigned full transparency (α = 0), the system can simulate the visual effect of virtual objects being obscured by transparent objects. Furthermore, by integrating high-precision environmental models and spatial information provided by 3D GIS, transparent virtual occluders can be precisely aligned with their corresponding real-world counterparts. This alignment produces the effect of being realistically occluded by real-world objects,, thereby enhancing both the realism and the immersive quality of AR systems.

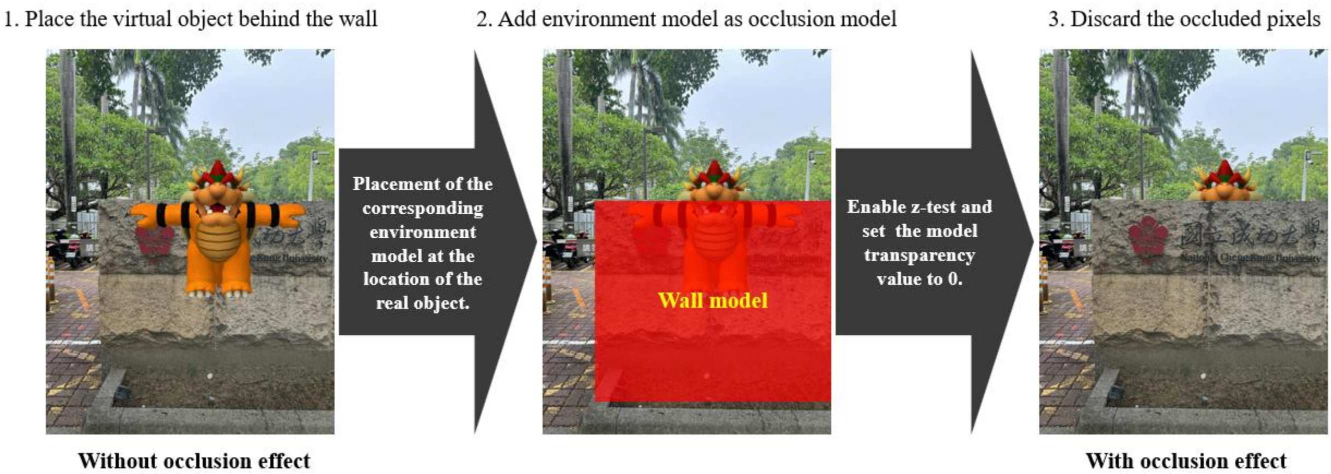


Figure 3: Illustration of occlusion effect activation.

Results and Discussion

This study adopts a university campus as the experimental site and integrates extended reality (XR) technologies with web-based approaches. By employing VR and AR to simulate the installation of solar panels on the department building's rooftop, it further investigates the potential visual impacts of such installations on the surrounding landscape. This section first explains the operational logic of the proposed system architecture, then respectively introduces the actual data sources and operational procedures. Finally, based on the proposed system architecture, the VR and AR implementation results are presented, followed by a discussion of the results.

a. System architecture

In the current era of ubiquitous mobile devices, integrating XR outcomes with the Internet allows the general public to access immersive and interactive experiences directly through a web browser, without the need to download additional applications. This approach enables the presentation of traditional GIS data in a more engaging and interactive manner, effectively expanding both its application scope and user groups. Therefore, to establish a web-based XR system, this study developed a comprehensive network system architecture. The overall operational logic is as follows: on the front-end, the system utilizes the positional and attribute data provided by the 3D GIS to configure the 3D scenes layout and perform computer-graphics rendering computations. Once the scene rendering is completed, the system dynamically adjusts the virtual scene in response to the user's real-time state—such as touch events and changes in position or orientation. On the back-end, the system integrates real-time data provided by external data platforms via IoT connections. The relevant data are filtered according to the user's current location, processed, and then delivered to the front-end to support dynamic scene updates driven by real-time conditions. Finally, the front-end constructs the user interface according to the intended application mode, while the back-end delivers the requested services, together with the 3D GIS-based models and other static resources, to the user.

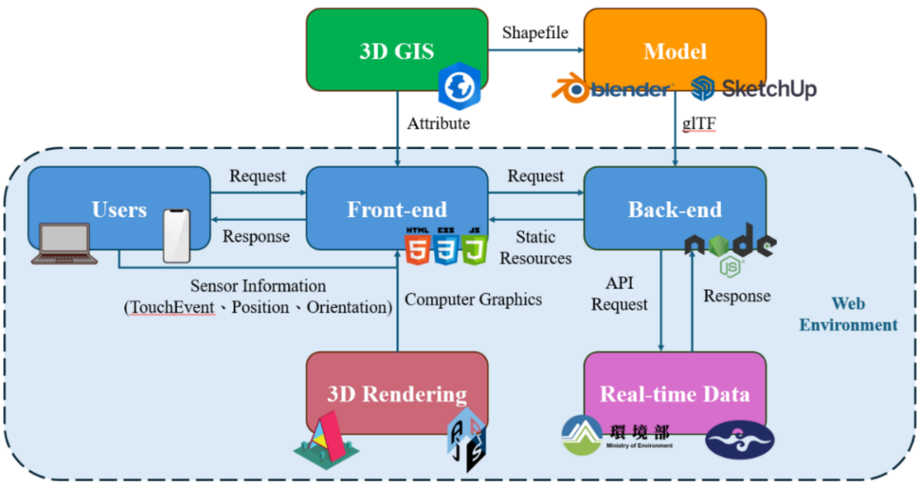


Figure 4: System architecture.

b. 3D GIS Data

The data used in this study were derived from the surveying results of the 2021 surveying camp conducted by the Department of Geomatics, National Cheng Kung University (NCKU), Taiwan. The study area covers a portion of the NCKU campus. The dataset includes the planar coordinates of all buildings, trees, walls, and pavements within the study area , expressed in the TWD97 coordinate system. Elevation information was obtained by calculating the differences between the Digital Surface Model (DSM) and the Digital Elevation Model (DEM). Subsequently, a comprehensive set of attribute data was established, including building names, building heights, number of floors, tree species, and tree heights. All datasets underwent accuracy and completeness validation and were represented as point, line, and polygonal features according to their spatial characteristics.

To render the TWD97 coordinate data for use in a VR environment, it was necessary to transform it into the coordinate system employed by the virtual world. Considering the relatively small extent of the study area and the absence of significant terrain undulation, elevation variation was ignored in this study. A four-parameter transformation was applied, using a known building corner point in the real world and its corresponding corner point in the virtual model as control points. The rotation angle, coordinate translation parameters, and scale factor required for transforming real-world coordinates into the virtual-world coordinate system were estimated using the least-squares adjustment method, thereby completing the planar coordinate transformation. On the other hand, for the AR applications, in order to facilitate integration with GPS-based positioning, the TWD97 coordinates were further transformed into the WGS84 geographic coordinate system. This served as the foundation for subsequent positioning and computational processes. Furthermore, since the rendering of virtual objects in computer graphics is based on their relative elevation with respect to the user's current position, the height of the user's handheld device must also be considered and subtracted. In this study, an average device height of 1.3 meters was adopted.

c. Model

In the model construction process, this study first imported base maps into modeling software (SketchUp and Blender) as references for 3D modeling , and subsequently loaded the building data from the 3D GIS. During model development, the negative z-axis was aligned with the north direction, and used the lower-left corner point as the model's origin. The primary structures of the buildings were extruded based on the height values recorded in the 3D GIS dataset, thereby establishing the main structure of buildings. Subsequently, additional building details—such as storage room, arcade, stairs—were incorporated. Materials and surface textures were applied by combining built-in resources from the modeling software, on-site photographic surveys, and Google Earth. Upon completion, the models were exported in glTF (Graphics Language Transmission Format). Compared to conventional 3D model formats, glTF files are lightweight and optimized for web transmission and real-time rendering, enabling rapid loading and efficient visualization in web environments.

Figure 5: Schematic representation of the model.

d. IoT and Real-time data

IoT serves as a dynamic bridge between the physical and virtual worlds by integrating diverse sensors to continuously collect environmental data—such as location, weather conditions, air quality, temperature, and movement trajectories—and transmits these real-time data streams to XR systems via web service. This mechanism not only supports real-time monitoring, simulation, and analysis in virtual environments but also enhances resource management efficiency and mitigates environmental impacts, thereby strengthening the realism and practical value of XR systems.

Therefore, this study incorporates APIs provided by the Taiwan Central Weather Administration Open Data Platform (https://opendata.cwa.gov.tw/index) and the Ministry of Environment Open Data Platform (https://data.moenv.gov.tw/). Through these services, real-time meteorological and environmental monitoring data—including weather phenomena, temperature, humidity, and air quality—are integrated to facilitate dynamic interactions between the physical and virtual worlds.

e. 3D Rendering

To ensure high-speed computation and real-time rendering of VR and AR scenes, the computer relies on the GPU to execute large-scale parallel processing. In the field of computer graphics, OpenGL (Open Graphics Library) is an application programming interface (API) that provides developers with a standardized interface to interact with low-level graphics hardware. With the development of web technologies, WebGL (Web Graphics Library) was introduced to enable 3D graphics rendering directly in web browsers. WebGL is a JavaScript API standard based on OpenGL ES 2.0, allowing 3D graphics to be executed and displayed in a web environment. Building on WebGL, three.js was developed as a high-level JavaScript library that simplifies the development process and enhances usability. three.js offers an object-oriented interface and modular functionalities, enabling developers to efficiently construct and manage 3D scenes.

In this study, the web-VR framework A-Frame was employed, which is a high-level web-VR framework built on top of three.js. Its main feature allows developers to rapidly generate 3D content using HTML-like syntax, employing an Entity-Component System (ECS) architecture to modularly manage scene elements and interactive behaviors. However, to implement AR functionality, the framework must be integrated with AR.js library, which is developed on top of three.js, A-Frame, and jsartoolkit5 (providing image- and marker-detection and tracking algorithms). This integration supports marker-based, image-based, and location-based AR techniques, enabling the rendering of AR objects by leveraging the user's current GPS position and camera pose information.

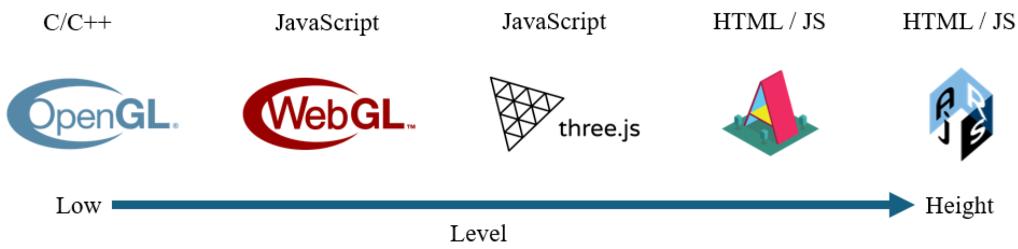


Figure 6: Relationship of computer graphics APIs.

f. VR Implementation Results

Building upon the aforementioned system architecture, this study successfully developed a Web-based XR system. As part of the implementation results, we first present the construction of the VR virtual campus. The system employed previously established 3D campus models together with virtual-world coordinates derived through a four-parameter transformation, and utilized the A-Frame framework to render the virtual-campus scene (Figure 7). Users can freely navigate and adjust their perspectives using a keyboard, mouse, or a mobile device in conjunction with on-screen controls. In addition, the system integrates other 3D GIS attribute data into the virtual objects, enabling users to access critical underlying information in an intuitive manner by simply clicking the objects, which is then displayed on an information panel (Figure 8), thereby significantly enhancing data visualization. Moreover, by leveraging real-time environmental data acquired via IoT connections (Figure 9), the system dynamically reflects these conditions within the virtual environment. For example, when the weather condition is set to rainy, the scene automatically switches to a rainy mode (Figure 10); similarly, when air quality deteriorates, a fog-like visual effect is applied (Figure 11), thus achieving real-time interaction between the virtual scene and real-world environmental conditions.

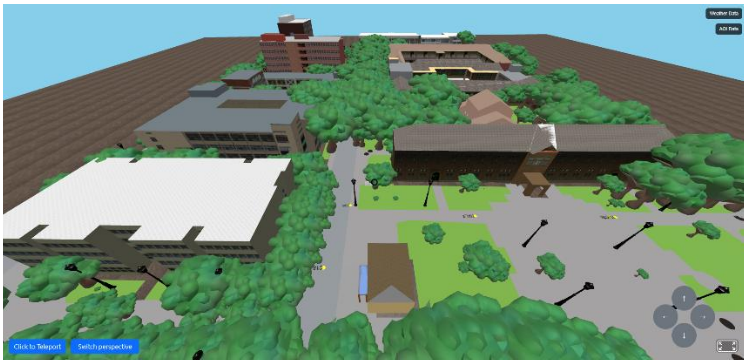
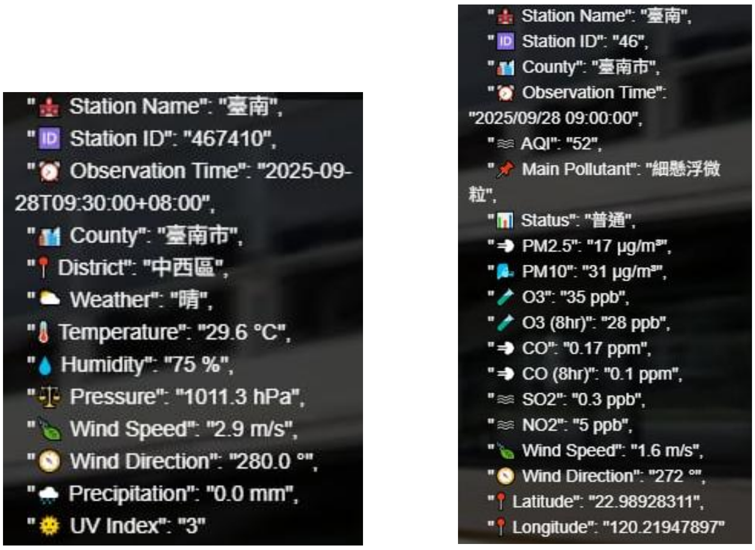


Figure 7: (Left) Results of the VR virtual campus construction.

Figure 8: (Right) VR information panel functionality.



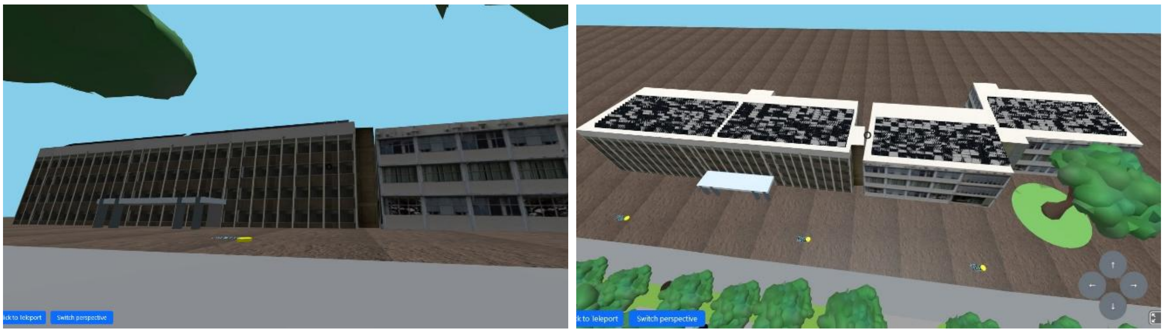
（a） （b）

Figure 9: Real-time data (a) Central Weather Administration (b) Ministry of Environment.


Figure 10: (Left) Rainy mode.

Figure 11: (Right) Haze effect mode.

Benefiting from the high-precision and comprehensive spatial data provided by 3D GIS, this study was able to faithfully reproduce occlusion effects observed in the real-world environment within the virtual world. Furthermore, additional virtual objects can be incorporated as needed to assess their potential visual impacts on the actual environment. For example, this system was employed to simulate the scenario of installing solar panels on the rooftop of the department building (Figure 12), leveraging the features of the VR platform to enable users to freely switch between aerial and ground-level first-person perspectives via toggle buttons, or to quickly teleport to designated scene locations by clicking on a virtual map (Figure 13), thus accommodating occlusion assessment from various perspectives. In this manner, the system allows for the pre- simulation of potential visual impacts on the surrounding landscapes from various perspectives within the virtual environment, serving as a reference for subsequent decision-making. However, the accuracy of such simulations depends on a complete and precise representation of occlusion. If virtual objects are not correctly constructed—including their geometry, position, and scale—or are entirely absent, erroneous occlusion effects may arise, thereby compromising the reliability of subsequent decisions.



(a) (b)

Figure 12: Simulation of solar panel placement in VR: (a) aerial perspective (b) first-person perspective.

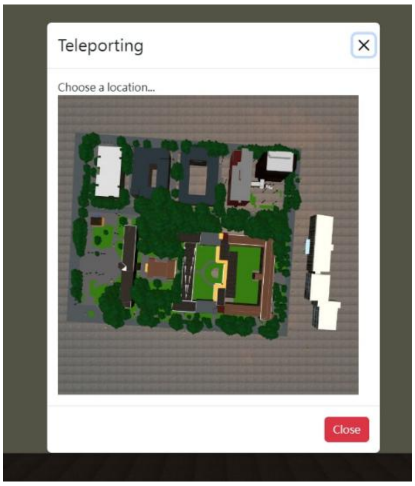
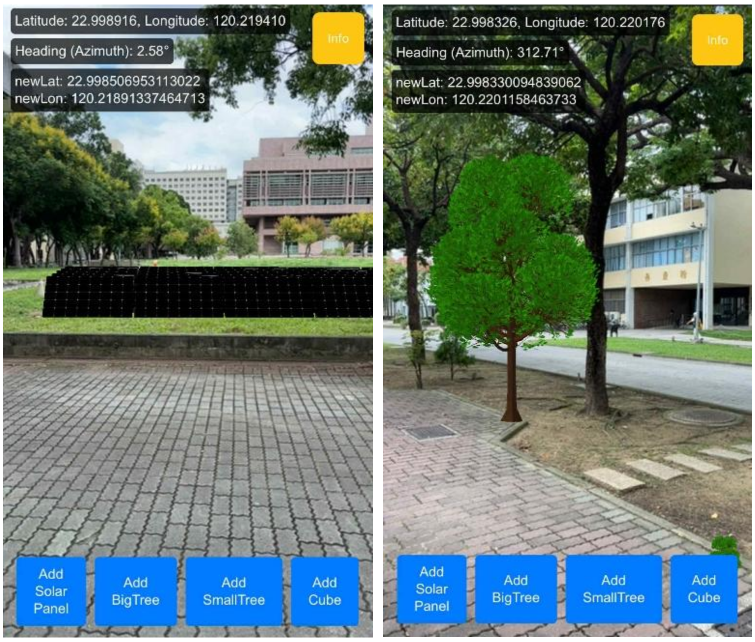


Figure 13: VR scene location teleportation functionality.

g. AR Implementation Results

In the AR implementation results, users can easily access the system through a web browser on any device equipped with a camera and GPS functionality. The system not only overlays essential 3D GIS information—including text, images, and 3D models—onto the real-world environment (Figure 14) to provide real-time, on-site information support, but also allows users to control the display of such information through toggle buttons to prevent interface clutter. Moreover, the system enables users to manually add solar panels or other virtual objects (Figure 15), allowing them to drag and rotate the virtual models directly within the scene and save the final placement results back into the 3D GIS database for subsequent applications. This functionality effectively realizes two core capabilities of AR: on-site data simulation and on-site data collection.

Figure 14: AR 3D GIS information.



(a) (b)

Figure 15: AR manual addition functionality.

Focusing on the core topic of this study—the occlusion problem—it can be observed that, when the occlusion effect is disabled, the solar-panel model appears to float unnaturally in front of the department building and other surrounding features

(Figure 16 (a)). In contrast, when the occlusion functionality is enabled, the portions of the solar panel that overlap with the building in the user's screen are correctly rendered as occluded (Figure 16 (b)), thereby producing a visual effect as if the panels were physically placed on the building's surface and substantially enhancing the realism of the scene simulation.

(a) (b)

Figure 16: AR implementation: (a) without the occlusion effect; (b) with the occlusion effect.

h. Questions and Discussion

From the perspectives of 3D GIS and occlusion, this study discusses how existing data and computer graphics techniques can be applied to address the occlusion problem encountered in XR environments. Based on the proposed methodology and system architecture, a VR and AR campus application system was subsequently developed and implemented. Nevertheless, several challenges and areas for improvement were identified during the research process. First, one issue observed concerns the occurrence of *z-fighting* during rendering. This phenomenon typically arises when two objects are positioned in extremely close proximity and viewed from a considerable distance. Due to the limited precision of the depth buffer, the algorithm cannot accurately determine which object's pixels should be rendered in the foreground, thereby resulting in flickering overlaps. As shown in Figure 17 (a), in the VR environment, when viewing the ground and the grass from an aerial perspective, a flickering effect occurs due to the close proximity of the two surfaces. Similarly, in the AR environment (Figure 17 (b)), when the solar panels are positioned at a certain distance from the user, their textures and geometry also exhibit noticeable flickering.

（a） （b）

Figure 17: The z-fighting phenomenon in (a) VR and (b) AR.

Second, since this study adopts a web browser as the user interface to provide XR experiences for the general public, the transmission of large volumes of 3D model data over the network may lead to significant loading delays when the number or file size of models is excessive. This challenge is particularly pronounced in VR applications, where, in addition to building models, supplementary elements such as roads, flowerbeds, trees, and streetlights must also be fully rendered, further increasing the computational burden.

Third, concerning AR positioning accuracy and completeness of occlusion, the system currently relies solely on GPS for spatial localization. Consequently, external factors such as sky visibility, multipath effects, and satellite geometry may lead to positioning errors or object drifting. Moreover, while this study employed a model-based method to address occlusion, if the scene content is incomplete, the environmental model lacks sufficient accuracy, or dynamic objects (e.g., foliage, vehicles) are present, the occlusion relationships cannot be accurately represented, which may consequently affect the users' sense of realism.

Figure 18: Challenges in AR positioning accuracy and completeness of occlusion.

Regarding the first two challenges, future work could consider adopting a game engine as the development platform to enhance depth buffer precision, and implementing the system as an APP that utilizes built-in model resources, thereby reducing reliance on network-based data transmission. However, such an approach would forfeit the advantages of real-time accessibility and cross-platform compatibility inherent to web-based solutions. With regard to AR positioning accuracy and occlusion completeness, future improvements may involve integrating high-precision positioning technologies (e.g., RTK [Real-Time Kinematic], UWB) with depth-sensing devices (e.g., LiDAR, stereo cameras) or AI-based image recognition methods, thereby enhancing both accuracy and functionality. Nevertheless, as discussed in the literature review, such integrations remain technically challenging. In conclusion, this research demonstrates that the core challenge extends beyond software design and development alone. It equally lies in the precision and stability of hardware devices, as well as the ability to achieve seamless integration across both hardware and software dimensions.

Conclusion and Recommendation

XR technologies, encompassing VR, AR, and MR, are emerging as critical bridges that connect the physical and virtual environments. With demonstrated potential across domains such as smart cities, education, healthcare, and industry, the core value of XR lies in its ability to achieve seamless integration of real and virtual worlds. By combining highly realistic 3D environmental models with real-time contextual data, XR enables users to better comprehend spatial information and gain decision-making support. However, the accurate representation of spatial positions and visual occlusion relationships between real and virtual elements—particularly the resolution of the occlusion problem—remains a key determinant of successful virtual–real fusion. If the occlusion relationships are not fully and accurately represented within the virtual environment, not only will the sense of realism for the user be lost, but simulation results may also become erroneous, potentially impacting subsequent decision-making.

This study first analyzed the differences in design considerations for VR and AR systems from both user and developer perspectives. Based on the proposed methodology, high-precision virtual environmental models were successfully constructed by integrating existing 3D GIS datasets with modeling software. Through coordinate transformation, real-world geographic coordinates were projected into the VR environment, thereby realizing a highly realistic VR system. Furthermore, by incorporating user location data, the AR system could capture the relative spatial relationships among virtual objects, real-world objects, and the user. A model-based approach was then applied to detect real-world objects occluding virtual objects, with computer graphics rendering techniques used to remove the corresponding pixels, thus establishing correct visual relationships between real and virtual objects. Finally, the developed VR and AR systems were enhanced with attribute integration, real-time environmental data, and multiple interactive functionalities, ultimately forming a more comprehensive XR system. A web-based system architecture was also implemented, enabling the general public to easily experience the fusion of virtual and real environments through a browser. In particular, by addressing the occlusion problem, the system accurately reconstructs the spatial relationships from the real world within the VR environment and ensures correct visual occlusion between AR virtual objects and real-world objects, thereby demonstrating that the integration of XR technologies with 3D GIS can effectively enhance both the realism and the accuracy of scene simulations.

In summary, this research proposes a strategy for leveraging 3D GIS data to address the occlusion problem and validates its feasibility and effectiveness through a real-world campus case study. While certain limitations and areas for refinement remain, the study represents an important first step in applying 3D GIS techniques to XR, demonstrating both the potential and value of solving occlusion challenges in real-world contexts. Moreover, this work lays the foundation for broader applications in domains such as smart cities, smart manufacturing, scenario simulation, and digital twins. Looking ahead, XR applications may be further enriched through integration with AI, BIM (Building Information Modeling), and diverse sensor data. As related technologies continue to advance, XR technology is bound to consistently provide users with novel and increasingly seamless virtual–real integration experiences.

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