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Research Article

Augmented virtual reality and 360 spatial visualization for supporting user-engaged design

Jin-Kook Lee [1], Sanghoon Lee[1], Young-chae Kim[1], Sumin Kim[2] and Seung-Wan Hong[3,*]

[1]Department of Interior Architecture and Built Environment, Yonsei University, Seoul 03722, Republic of Korea
[2]Department of Architecture & Architectural Engineering, Yonsei University, Seoul 03722, Republic of Korea
[3]Department of Architecture, Inha University, Incheon 22212, Republic of Korea
*Corresponding author. E-mail:hongsw@inha.ac.kr (SH)

Abstract

This paper discusses an approach to augmented virtual reality (AVR) and 360-degree spatial visualization. The approach involves locating stereoscopic three-dimensional virtual objects into a real off-site panorama, supporting spatial remodel design decision-making through realistic comparisons. Previous studies have shown that in the design process, end-user engagement promotes the quality and satisfaction of design solutions. Immersive media such as virtual reality (VR) and augmented reality (AR) have increasingly been used as communication tools for user engagement in design, as they provide intuitive and realistic user experiences, particularly in comparing design plans. However, the dichotomous affordance of current VR and AR devices is limited in satisfying both the sense of realism and immersion that are essential for user engagement. To overcome this shortcoming, we propose an AVR-based design visualization approach that integrates the advantages of both media technologies to provide a high sense of realism and immersion off-site, responding to location and environmental stimuli, such as lighting, material, and other factors. To achieve this goal, we used 360-degree panorama data of the target space as a design visualization background, with content immersion experienced through VR hardware. Additionally, we developed software to demonstrate the actual use of the AVR-based approach, and various visualization-purposed file formats can be exported automatically using this software. The software supports the authoring of 360-degree spatial visualization videos for realistic design comparisons, which can be easily accessed by end-users using a head-mounted display or smartphone, even in real-time. We performed a demonstration of this approach using an actual remodel design project for the university library lobby, and this paper shows the usability and applicability of the AVR-based approach for user engagement.

Keywords: augmented virtual reality, 360-degree spatial visualization, comparing design alternatives, end-user engagement, design decision support

1. Introduction

User engagement in design involves direct participation of users in architectural processes, such as design, operation, and maintenance, which can improve the final result (Sanoff, 1999). End-user review of the design can improve their satisfaction with the final result, building performance, and economic efficiency because changes in the building design after construction are relatively limited (Bullinger *et al.*, 2010; Zahedi *et al.*, 2011). Conventionally, various methods, such as design charettes, public hearings, workshops, and surveys are used for design communication to achieve user engagement in design (Bullinger *et al.*, 2010). Among the various communication media used in this process, visual media, such as drawings and rendered images have been primarily employed between participants to convey design information (Zahedi *et al.*, 2011). However, fully delivering design ideas or intentions to the client off-site is difficult using conventional design communications, because many concepts are usually presented as two-dimensional (2D), projecting three-dimensional (3D) spatial information onto a plane.

The recent development of immersive media technologies, such as virtual reality (VR) and augmented reality (AR), provides a 3D immersive experience of the design to users (Bullinger *et al.*, 2010; Kalay, 2004). Users can experience the design information on a real scale using immersive media to deliver the design information more intuitively (Liu *et al.*, 2021). These features are used in the architecture, engineering, construction, and facility management (AEC/FM) industry in multiple ways, such as design review and occupant behavior simulation (Abd-Alhamid *et al.*, 2019; Cha *et al.*, 2019; Olbina & Glick, 2022; Yeom *et al.*, 2020). Moreover, VR is mediated through the virtual building environment, which is comprised of digital data.

Architecture and interior design are initiated from a plethora of dynamic clues on-site. Representing the virtual environment inherently involves an abstraction of reality; thus, the abstraction cannot reflect all subtle stimuli in the real on-site (Kalay, 2004). This means that while virtual environments can mimic real-world conditions, they have difficulty delivering a high degree of realism (Eiris *et al.*, 2018). However, AR could provide a high degree of realism with the surrounding situation information because it superimposes digital data on a view of the real world on-site (Dan *et al.*, 2021; Lee & Yoo, 2021). Nonetheless, the AR head-mounted display (HMD) currently has low hardware performance, such as the field of view (FoV), which is lower than that of the VR HMD. Previous studies have noted that such hardware limitations cause a

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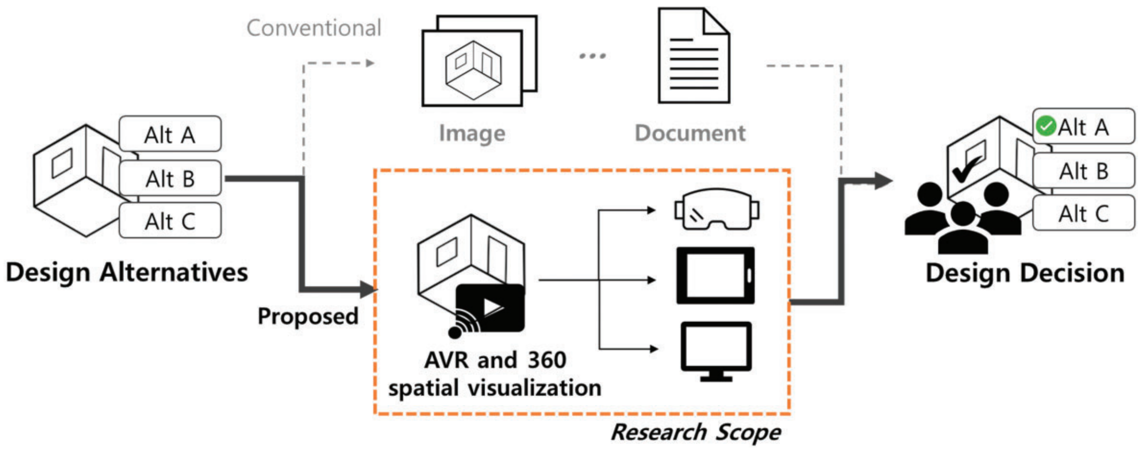

Figure 1: Research overview and scope.

partial, discontinuous perception and incongruent synchronization between 3D virtual objects and the authentic off-site, which hinder designers' analysis and a sense of immersion (Dan *et al.*, 2021). Therefore, current VR and AR-based user engagement in design has limitations in providing a high sense of both realism and an immersive experience, which are essential to providing an intuitive experience (Brivio *et al.*, 2021; Kim *et al.*, 2021; Shin & Lee, 2019). To promote both realism and immersion, we aim to support users' holistic, seamless perception and graphical synchronization between 3D virtual objects and off-site.

To achieve the goal, we propose and demonstrate an approach to visualize interior design alternatives off-site with a high sense of realism and immersion for design decision support. Our approach uses augmented virtual reality (AVR) to integrate the benefits of both VR and AR. We use 360 panorama data as a realistic visualization background for design, and a VR device to provide an immersive experience. The 360 panorama captures everything surrounding the capturing position, providing users with a "sense of presence" that is highly realistic and immersive even without visiting the site (Bourke, 2014; Brivio *et al.*, 2021). We demonstrate the potential of this AVR-based approach to support design decisions using the 360 spatial visualization method. Among the various application scenarios of the AVR-based design, we have adopted 360 panorama video platforms. While 360 panorama images require additional platform development to share and update, online video platforms are already popular and support convenient utilization of VR/AR hardware. Thus, panoramic video platforms enable multiple users to access design alternatives simultaneously from off-site. The scope of our paper is to describe the applicability of AVR, without systematic investigations into the empirical effects of this application. We focused on proposing a combination of VR and AR methodology relying on the process of technical implementation. The demonstration implemented AVR to visualize alternative interior design options for the lobby area within an existing building (Fig. 1).

2. Background

2.1. Design communication media for user engagement

The design process involves collaboration among multiple stakeholders, including designers, clients, and constructors, to achieve optimal design results through communication media (Pile, 1995). Communication between the designer and end-user is one of the key factors for improving satisfaction, building performance, and cost-efficiency in the design process. As user requirements are diverse, multiple efforts have been made to collect and respond to user requirements using various participation techniques, such as the user-centered design approach (ISO 13407, 1999).

For this purpose, multiple methods, such as design charettes, public hearings, surveys, and design reviews have been used for user engagement in design (Bullinger *et al.*, 2010). Considerable communication media are available in the design process, such as voice, text, and images. Selecting the appropriate communication media for each method is crucial in efficiently delivering design information (Kalay, 2004), as it can reduce unnecessary time-consuming and costly work, such as design changes caused by miscommunication. Additionally, changes in the building design after construction are limited (Bullinger *et al.*, 2010; Zahedi *et al.*, 2011).

For user engagement in design, it is important that they understand the 3D spatial design information. Visual media, such as sketches, computer-aided design-based 2D drawings, 3D models, and photorealistic rendered images, have been primarily used to efficiently express and deliver complex 3D spatial design information due to the development of digital design and interface technology (Kalay, 2004).

However, the use of symbols in 2D drawings limits the delivery of design information to end users who are unfamiliar with them (Barrett & Stanley, 1999). Moreover, conventional visual media projects 3D spatial information onto 2D media, such as paper and monitors, making it more difficult to express complex designs using 2D-based media.

Immersive media technology, such as VR and AR, could provide intuitive visualization and experience for design information. Therefore, such technology could be used as a visualization medium for digital mock-ups to support design communication (Cheng *et al.*, 2020; Maldovan *et al.*, 2006). As design communication is broad and conducted throughout the entire design process, previous studies have focused on using design communication to deliver design information to end-users.

2.2. Immersive media in the AEC/FM industry

The use of immersive media, such as VR and AR, can provide users with realistic experiences by offering multimodal sensory information (Eiris Pereira *et al.*, 2017). VR is a digital interface that provides users with real and immersive experiences by stimulating their senses, such as sight and hearing, in a virtual environment consisting of digital data (Cheng *et al.*, 2020; Zhang *et al.*, 2022). Because VR consists of digital data, the virtual environment is separate from reality and is not constrained by safety or spatial limitations in the physical world. As a result, VR can allow users to experience phenomena that are difficult to experience in reality (Westerdahl *et al.*, 2006). Nonetheless, AR is an interface that superimposes digital data onto the real world, enabling users to experience contextual information of their surrounding environment and facilitating realistic experiences and interactions. Azuma (1997) described three characteristics of AR: (i) combining virtual data with the real environment, (ii) supporting real-time interaction, and (iii) placing it on 3D coordinates. Furthermore, AR provides visualization and interaction with virtual objects in the real world, thus having the potential to enhance users' understanding of surrounding space information (Azuma, 1997). Both VR and AR offer the advantage of providing intuitive information and experiences to users, which has led to their widespread use in various fields, such as the arts, cultural heritage management, business and marketing, psychological diagnosis, physical and mental rehabilitation, assembly and operation, training, tourism, education, military, and medical applications, such as anxiety reduction, phobia treatment, addiction training, pain distraction (Liberatore & Wagner, 2021; Olbina & Glick, 2022).

At all stages of the AEC/FM industry, immersive media have also been used (Olbina & Glick, 2022). Moreover, VR technology is used to simulate evacuations in emergencies such as fires, which are difficult to experiment with for safety reasons (Cao *et al.*, 2019; Lin *et al.*, 2020), and for construction safety education (Habibnezhad *et al.*, 2020; You *et al.*, 2018). In addition, because the virtual environment used for VR comprises digital data, it is easy to create an environment that can control variables for the experiment. Therefore, a few studies have been conducted to experiment with occupant behavior or reactions to architectural elements, such as ceilings, windows, and lighting (Cha *et al.*, 2019; Heydarian *et al.*, 2015; Hong *et al.*, 2019). However, VR is limited in providing users with a high degree of realism because the virtual environment consists of digitally generated data. Inherently, constructing the virtual environment involves arbitrary abstraction from reality (Kalay, 2004). Indeed, VR requires interfaces or devices to perceive and calibrate the spatial depth between users' physical locations and virtual objects (Loyola, 2018).

Furthermore, AR is used as a visualization medium in the real world with design information, such as 3D design models, air fluids, and structures (Fukuda *et al.*, 2019; Liu & Seipel, 2018; Olsson *et al.*, 2012). In addition, AR is used for construction management to compare digital models and actual construction situations (Behzadan & Kamat, 2013; Wang & Dunston, 2007). It is also being studied to provide the information necessary for operation and maintenance, such as fire extinguishers (Cheng *et al.*, 2020; Dunston *et al.*, 2011). Moreover, AR mediates the real world for visualization to provide a realistic experience to users. However, at present, AR has location dependency, which requires a visit to the site for the experience, and the visualization result could vary depending on the site conditions, such as lighting.

2.3. Immersive media for user engagement in design

Previous studies have investigated the effectiveness of realistic media in facilitating user participation in the design stage. For instance, VR has been used as a visualization tool for 3D design models or as a substitute for actual mock-ups in various buildings, such as hospitals, courts, and houses, to enable design review with end users (Dunston *et al.*, 2011; Maldovan *et al.*, 2006). A few studies have incorporated the virtual environment into the user-centered design process to evaluate designs with end users (Bullinger *et al.*, 2010; Westerdahl *et al.*, 2006). Additionally, a previous study found that VR enables residents to directly participate in the design process, leading to better understanding and clearer opinions (Loyola *et al.*, 2019).

Furthermore, a few studies have examined user engagement in interior design. For instance, user opinions on material selection were collected based on a visualized virtual environment, which was reflected in the final material selection (Zhang *et al.*, 2019). Another study was conducted to understand the spatial perception of architectural 3D models in an immersive VR environment (Paes *et al.*, 2017). A study on user preference for lighting design in an indoor office using a virtual environment was also conducted (Heydarian *et al.*, 2017). In addition, studies have investigated whether visualizing energy consumption information or lighting distribution is effective for user decision-making (Carneiro *et al.*, 2019). Through the use of virtual environments, users can experience and provide feedback on design elements. VR has been applied in architecture and interior design as a method for participatory design, iteration on materials and interior facilities, and users' way-finding. Previous studies addressed have shown the strong applicability of VR for evaluating interior design alternatives, including holistic forms, materials, and interior facilities. Regarding AR-based user engagement in urban design, AR has been used for decision support in urban design problem reviews with multi-user participation (Schubert *et al.*, 2015). Mobile AR-based visualization of building design has been studied for design decision support in building design engagement (Olsson *et al.*, 2012). In addition, a study was conducted on end-user design review by visualizing façade design using smartphone-based AR (Allen *et al.*, 2011). An interaction method was proposed through AR-based visualization so that users without domain knowledge could directly participate in the design process to reflect design requirements (Byun, 2003).

Through immersive media, design information is delivered intuitively, and users can better understand it and express their opinions. In this process, the importance of devices that can allow for the experience of various sensory experiences is also emphasized. Both VR and AR technologies can provide users with an immersive experience and deliver design information more effectively. To achieve an immersive experience, the type and performance of the hardware used to interact with visual content are also important.

2.4. Future direction: AVR in indoor space

VR and AR devices are used to provide immersive experiences to users, and they are categorized into three types based on the display: desktop, handheld, and HMD (Cheng *et al.*, 2020). Desktop displays rely on high computing power but offer low portability. Handheld displays provide high portability and use a smartphone or tablet. The HMD is mounted on the head and displays content directly in front of the eyes, making it the most suitable for providing users with immersion (Passmore *et al.*, 2016). The two main types of HMDs, VR and AR, have different hardware limitations. While state-of-the-art VR headsets (e.g., Quest Pro and HTC Vive Pro Eye) have an FoV between 110 and 115 degrees, AR headsets are far more limited at 50–52 degrees (e.g., Hololens 2 and Magicleap One).

Many applications using VR and AR for architectural design visualization are being developed and used. Recently, devices with

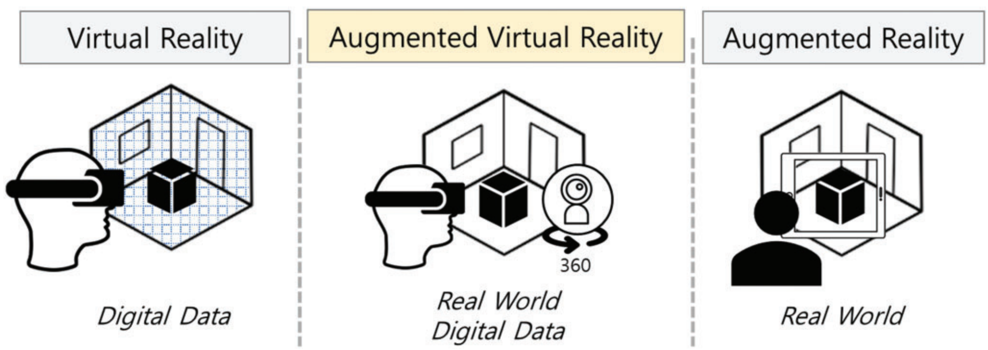

Figure 2: Concept of AVR.

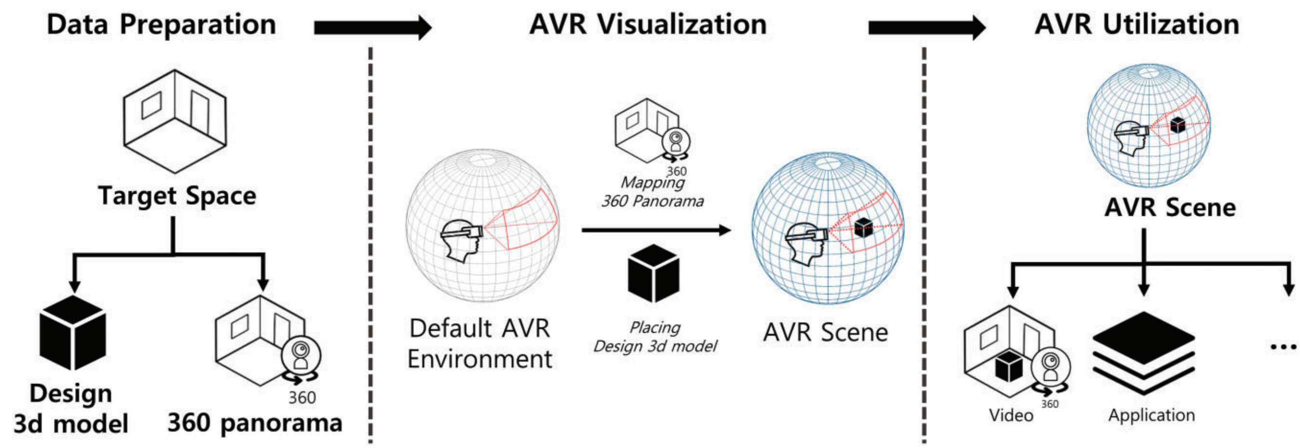

Figure 3: Overview of AVR-based design visualization process.

lidar sensors, such as the iPad Pro 4 tablets, can acquire depth data in space within a short distance, allowing users to experience off-site circumstances realistically. The application is used as a plug-in for the design authoring software or produced as a web-based application that does not require additional installation to experience VR and AR content easily. Additionally, applications with specific purposes and functions are used in mobile and HMD hardware.

In summary, the VR HMD device provides a highly immersive experience but lacks realism because it comprises digital data that mimic the real world. In contrast, AR could provide a realistic experience using a natural background. However, AR HMD devices currently have limitations in providing immersive experiences due to factors such as the narrow FoV or location dependency.

Recently, an implementation has been conducted to visualize architectural data using 360 panoramas to complement the realism of VR. The 360 panorama seamlessly provides visual information around the capturing point, enabling the experience of being there (Bourke, 2014). Visualization of underground and underground pipes in building facilities has also been studied (Côté, 2011; Côté *et al.*, 2013). The Building Information Modeling (BIM) model is visualized based on the image transmitted from the field using the position of the 360 camera (Gheisari *et al.*, 2016). For construction, using 360 panoramic images for safety training has been explored as a means of achieving reality and reducing modeling time and cost, which is currently performed in VR (Eiris *et al.*, 2018; Kaplan-Rakowski & Meseberg, 2018). However, previous studies have focused only on visualizing digital data through 360 panorama images off-site. Moreover, few studies have focused on design decision support for multiple end-users in the design stages and immersive experiences using VR devices with panorama-based content.

For previous research using 360 panoramas, different terms, such as semi-AR (Gheisari *et al.*, 2016) and augmented panorama (Eiris *et al.*, 2018), have been used depending on the researcher, and these terms are not defined as a single unified term. Therefore, in our paper, an approach that integrates the advantages of the sense of realism in AR and the immersion in VR using 360 panoramas as a visualization background and providing immersive experiences through VR hardware is defined as AVR.

Conventionally, AR contains a high amount of real content but a low amount of virtual content. Therefore, AR has the potential to be used for an existing indoor space for a realistic experience (Dan *et al.*, 2021). Similarly, in indoor space, AVR could save time and money for modeling the surrounding environment based on visual and auditory context information collected based on 360 panoramic images of the target space and can be used for a realistic visualization of the design (Fig. 2).

3. Methodology: AVR-based Design Visualization Process

3.1. Overall process

This section describes the process of visualizing designs using AVR. The aim of AVR is to provide users with a sense of realism and immersion off-site. To achieve this goal, the 3D design model is

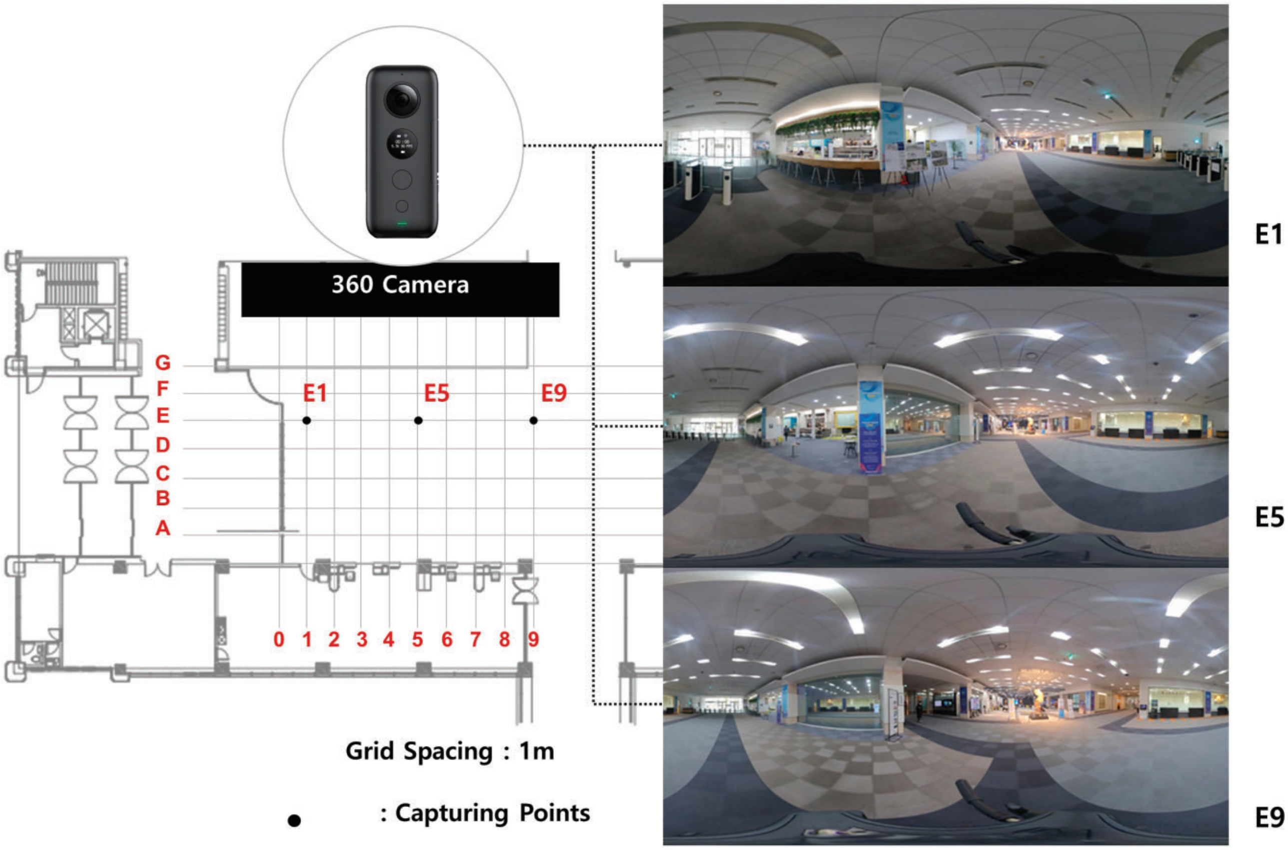

Figure 4: Example of interior 360 panorama using 360 camera (Insta 360 One X).

Figure 5: Example of AVR-based design visualization in a game engine (left-hand panel) and device (right-hand panel).

visualized on a 360 panorama image or video captured in the target space. The AVR-based design visualization process is divided into the following three stages (Fig. 3):

(i) Data preparation: Prepare the 3D design model and 360 panorama images or videos for visualization. Users can author 3D design models using various tools and formats. One or more 360 panorama images or videos need to be captured or generated in high resolution using a 360 camera or renderer.
(ii) AVR visualization: Author an AVR scene by mapping the 360 panorama data to the default AVR environment and placing the 3D design model. The default AVR environment is created by placing a camera at the center of a sphere.
(iii) AVR utilization: Use the AVR scene authored in the previous stage. In the developed system, the AVR scene can be used in various types of data, such as standalone applications or videos, considering the hardware platform and utilization scenario. Post-processing, such as adding interactions or interfaces, may be required depending on the utilization scenario.

Recently, there have been various methods available for authoring immersive media content. For example, web-based platforms

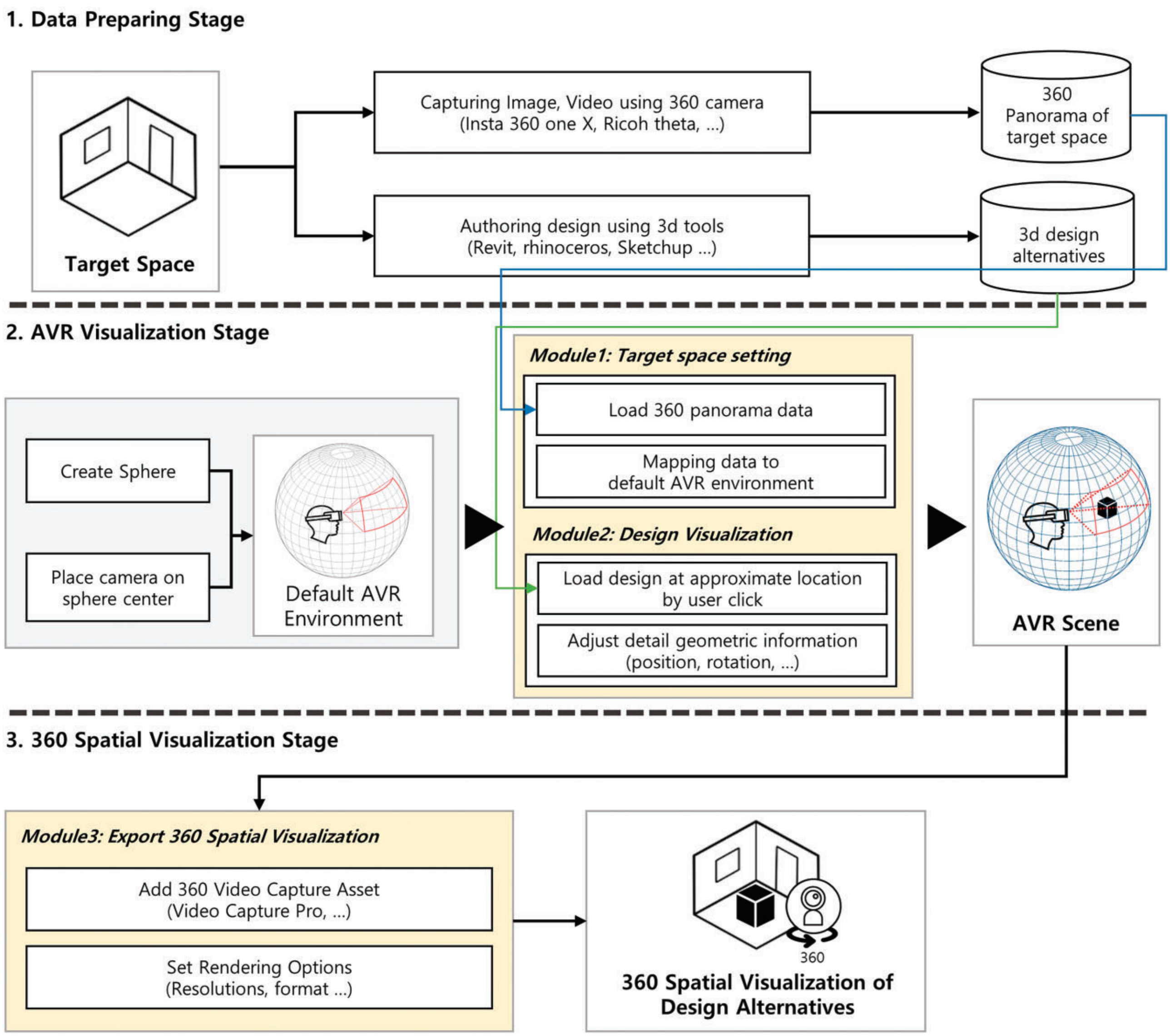

Figure 6: Overview of AVR-based 360 spatial visualization process.

like Amazon Sumerian, frameworks such as Argon.js, and standalone software like Unity 3D or Unreal Engine can be used. We chose to implement the AVR using Unity 3D, a game engine, due to its vast libraries and ease of deployment. This game engine also supports distribution to various platforms, including Windows, Mac, Android, iOS, and more (Unity Engine AEC Overview & User Manual, 2023).

3.2. Data preparation

The data required for AVR visualization is primarily divided into a 3D design model and 360 panorama data of the target site. Conventionally, design is considered a wicked problem that cannot be clearly defined (Song *et al.*, 2020) because each project could vary depending on conditions, such as the target space, client requirements, building codes, and designer experience (Song *et al.*, 2020). Furthermore, there are various software options available for authoring 3D models. Therefore, authoring the 3D design model is outside the scope of this paper.

We focus only on preparing 360 panorama images and videos used as the background environment. AR provides a realistic experience by composing digital data with real-world data on-site. In our paper, AVR aims to provide a sense of realism without physically visiting the site, using 360 panorama data that contains the spatial information of the target space. This is because 360 panorama data contains omnidirectional spatial information centered on the capturing point. At the data preparation step, 360 panoramas can be acquired by stitching a series of images of the target space. Recently, 360 cameras such as Insta 360 and Ricoh Theta can simultaneously handle the stitching process using images acquired from multiple lenses. As hardware develops, the image resolution acquired using the 360 camera is increasing. In indoor spaces, 360 panoramas can provide a realistic experience without actually visiting the site, enabling users to experience the space.

Using 360 panoramic data, a user can pan the viewpoint at the capturing point. However, movement of the viewpoint is not recommended because it can cause quality deterioration, such as distortion, when moving or adjusting the height of the camera. Instead, dividing the indoor space into regular spaces and capturing multiple panorama data can support a transition

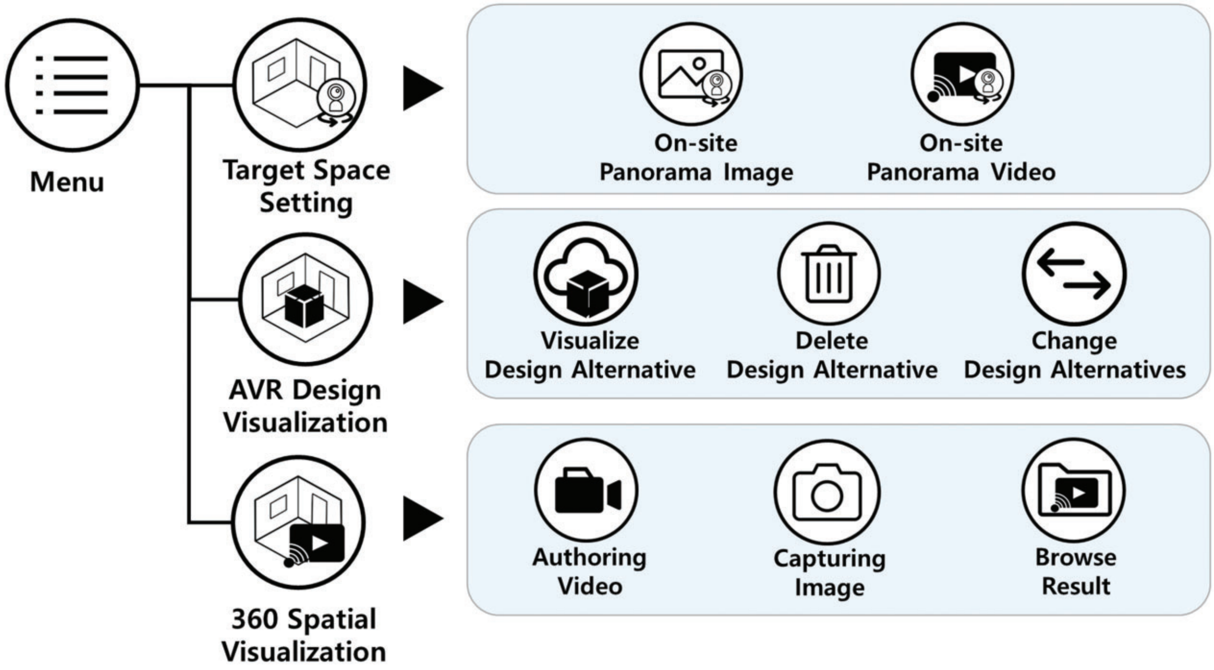

Figure 7: Structure of the prototype software menu.

between the captured panoramas. This transition enables users to experience movement within the target space, as illustrated in Fig. 4.

In this case, it is crucial to determine the appropriate spacing because, as the interval width becomes narrower, time and cost increase. In addition, it is necessary to collect the captured data at human eye level to provide users with a sense of being there in panoramic data.

Unlike AR, which can be constrained by site-specific conditions such as lighting or the amount of sunlight over time, which could limit its use in certain scenarios, AVR is relatively free in on-site conditions and can be collected under various circumstances. Because it uses the collected 360 panorama data as a background environment, it is possible to review designs in various scenarios using 360 panoramas captured under different conditions, such as day or night, with people or without people.

3.3. AVR visualization

Unity 3D provides ample libraries, functions, and custom scripts for authoring immersive media content. The 3D design model and panorama data collected in the previous stage can be loaded and visualized in the game engine. In the default option for creating an AVR environment, Unity 3D places a camera in the center of a virtual sphere. However, we used the cube-map format of panoramic videos due to its accurate mapping into a cube and ease of calibration for inserting geometry (Unity Engine AEC Overview & User Manual, 2023). After mapping the 360 panoramas to a skybox or individual geometry, it is possible to experience an on-site panorama by placing the camera at the center of the projected panoramas. We focus on the equirectangular format of the 360 panorama. With the target space background, users can load the 3D design model and place it in an appropriate position. The collected 3D design model can be loaded into the game engine in multiple file formats, such as FBX and OBJ. The process of matching is one of the critical factors for an immersive and realistic AR experience (Gheisari *et al.*, 2016; Unity Engine AEC Overview & User Manual, 2023).

Unlike existing AR, which matches digital data based on markers or feature points through a 3D reality space, AVR uses 2D 360 panorama data. Therefore, users are technically surrounded by a holistic 3D environment regardless of the limits of their view scope. The AVR software enables designers to adjust the direction, rotation, and size to visualize the 3D model inside a 360 panorama. Figure 5 depicts an example of a visualized design using AVR.

3.4. Utilization plan of AVR-based design visualization

We plan to utilize the AVR scene by placing 3D objects on a 360 panorama under different hardware scenarios. We can use the software development kit for each hardware and platform or a lidar sensor equipped in a mobile device to recognize the depth of the scene for realistic visualization. Unity 3D provides libraries and functions for user interactions, such as interface implementation, object properties, and custom scripts, to support various utilization scenarios (Unity Engine AEC Overview & User Manual, 2023). There are various ways to employ the AVR scene in design stages. For example, one can create a 360 spatial visualization video of a design alternative, visualize designs from a remote location by streaming a 360 panorama in real-time, or develop a standalone application that includes additional interactions for conducting design reviews off-site. Depending on the utilization scenario, post-processing for adding custom C# scripts or custom libraries could be required in Unity 3D.

Among the multiple scenarios, we describe the applicability of the AVR approach with 360 spatial visualization of design alternative scenarios. We developed a visualization software prototype that allows users to create a 360 video of design alternatives to demonstrate this scenario. Recently, video-sharing platforms that provide 360 video viewer functions, such as YouTube and

Table 1: Function description of software for 360 spatial visualization.

Category	Function name	Description
Target space set-ups	Coordinates/anchoring handler	Using appropriate platform and libraries, imported environmental images/videos can be located on appropriate coordinates by using user inputs or default values, based on sphere's center point, etc.
	On-site panorama images/videos	Set background environment of target space using on-site panorama images/videos.
AVR design visualization	Coordinates/anchoring handler	Using appropriate platform and libraries, imported 3D geometry (design model alternatives) can be anchored on appropriate coordinates by using user selected locations or default values.
	Visualize design alternative	Load design alternative from local or server-based file and place model on the background environment using 360 panoramas.
	Delete design alternative	Delete design alternatives visualized using the visualize design alternative function.
	Change design alternative	Change multiple design alternatives visualized in the AVR scenes.
Spatial design visualization and presentation-purposed file generation	Authoring videos	Export authored AVR video files in 360 panorama video form.
	Capturing images	Export authored AVR scene images in 360 panoramic views.
	Browse results, and general UI features	Open the folder where the authored image or video is saved, and general user interfaces including the handlers for the design presentation-purposed file generations.

Facebook, have been used for 360 experiences. Users can experience the authored immersive visualized 360 panorama video of design alternatives using the applications or webpages provided by each platform.

4. Results: AVR-based 360 Spatial Visualization of Interior Design Alternatives

4.1. AVR-based 360 spatial visualization process

Based on the AVR-based design visualization process described in Section 4, this section describes the AVR-based 360 spatial visualization process and prototype software for an immersive and realistic experience of design alternatives off-site. The process is implemented using the Unity 3D game engine, an overview of it is presented in Fig. 6. The process consists of three stages: data preparation, AVR visualization, and 360 spatial visualization, as displayed in Fig. 9. As each stage has been described in the previous section, this section presents the three modules for supporting AVR-based 360 spatial visualization:

(i) Target space setting module: This module sets up a target space environment based on the 360 panorama. The collected 360 panorama data can be loaded from a local file or server. This module loads 360 panorama data of the target space and maps it to the default AVR environment sphere to set the background environment and provide a sense of realism.
(ii) Design visualization module: This module authors the AVR scene by placing the design alternatives within the target space set by the previous module. Design alternatives can be obtained from both the server and local files, and the AssetBundle function can be employed for this purpose. AssetBundle is a function that enables 3D models, images, materials, and so on to be streamed from applications distributed through preprocessing in Unity 3D. Once the design alternative is loaded, the user can obtain the sphere-shaped 3D coordinates through an interface. The 3D design alternative is then placed on the approximate location using the obtained 3D coordinates. The detailed 3D coordinates and rotation of the design alternatives can be adjusted using the keyboard and mouse.
(iii) Export 360 spatial visualization module: This module authors the 360 spatial visualization using the AVR scene authored by the previous module. The module supports the distribution of equirectangular image or video formats, and enables users to adjust the rendering options, such as resolutions, quality, and format. An asset of Unity 3D is adopted to export the 360 panorama in a particular format. With this module, users can experience the 360 spatial visualization of the design alternatives on multiple video-sharing platforms through various hardware options, such as VR HMD, desktop, tablet, and smartphone.

4.2. Prototyping AVR-based 360 spatial visualization software

Based on the process and module discussed in the above section, AVR-based 360 spatial visualization prototype software was implemented for demonstration. The Unity 3D game engine was used for the implementation of the prototype software, which has the primary function of authoring 360 formats of design presentation images and videos from given on-site panoramas and 3D design alternatives.

The structure and functions of the interface implemented for 360 spatial visualization are presented in Fig. 7. Table 1 describes each function of the interface. Each function was implemented using basic Unity C# scripts. The prototype includes a graphical user interface (GUI) for AVR-based 360 spatial visualization, which was developed using the built-in tools in Unity 3D for GUI Development. Each function was implemented using the UI function with the basic functions of C#, and Unity can be assigned to the buttons, allowing users to use the functions implemented with the UI.

An example of the 360 spatial visualization process for interior design alternatives is illustrated in Fig. 8, as follows: (i) setting the target space environment using a 360 panorama video, (ii) visualizing the interior design alternative on the target space by allowing the user to click to place and adjust

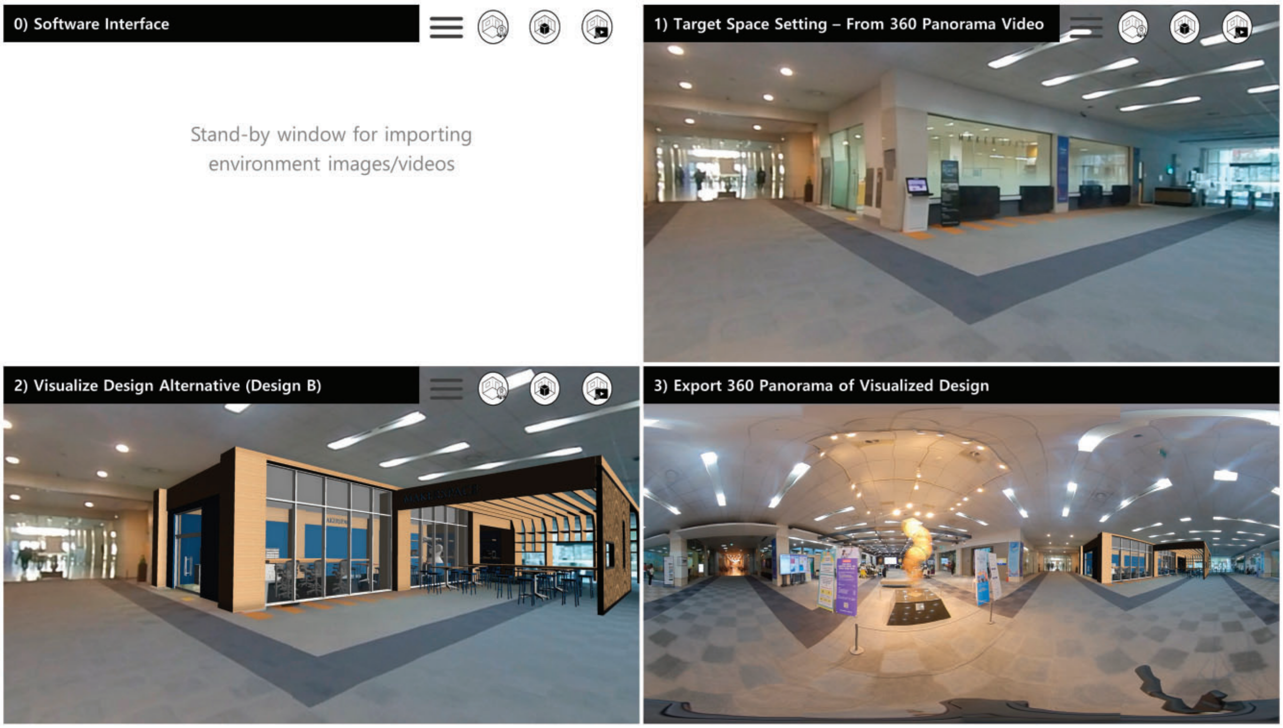

Figure 8: Snapshot of software demonstration scenarios.

detailed positions and rotate the design, and (iii) exporting the 360 panorama image or video of the visualized design. The video capture asset was used to export the 360 panorama video at runtime.

Through these video-sharing platforms and the 360 panorama viewer application, users can easily access and experience the 360 spatial visualization of a design. The visualization quality for each hardware could vary depending on the display performance, among other factors. Even though using a VR HMD device, such as Oculus Rift, could be more immersive for users, tablets or smartphones that are more accessible can also be used, depending on the situation and conditions.

4.3. Demonstration results of 360 design spatial visualization

In this section, a demonstration was performed using a remodeling scenario with the prototype software. The lobby space on the first floor of the Yonsei University Library in Seoul, Korea, was selected as the target space for the initial demonstration. A brief overview of the target space is displayed in Fig. 9. The target space is adjacent to the maker space and is currently only used as a passageway. Three design alternatives were modeled to improve and use the target space. Design A was designed to improve the spatial identity using the university's UI colors without changing the current space use. Design B was designed to expand the maker space, which is the current use of space in the adjacent space. Design C was designed as a collaboration space with a large screen installed to support long-distance collaboration by changing the use in the current space.

The 3D design alternatives were authored using Autodesk Revit to collect data for the AVR-based design visualization. The models were exported using the FBX format and were saved using the AssetBundle function in Unity 3D after post-processing. In addition, the 360 panorama video was captured from the target space using an Insta 360 One X. It supports saving up to 5.7k resolution of the 360 panorama video. The software demonstration was performed using the collected data. An overview of the target space and examples of the 360 spatial visualization results of the design alternatives are summarized in Fig. 8. As a result of the AVR-based 360 spatial visualization video, the space user movement and surrounding information of the target space can be checked along with the design.

4.4. Application of AVR and 360 spatial visualization

This section describes the application of AVR and the results of 360 spatial visualization. The 360 panorama videos produced as a result of the demonstration can be shared through a video-sharing platform or 360 viewer application, allowing multiple users to access them simultaneously without time or spatial constraints. Users can experience AVR-based design alternatives on various hardware types, such as VR HMDs, desktops, tablets, and smartphones, using a website or application. At this time, we used the Unity 3D plug-in to inject metadata from the 360 format to the video for utilizing video-sharing platforms, and Google's spatial media metadata injector was one of the easiest tools to use for this purpose.

Figure 10 shows an example of an uploaded 360 spatial visualization to the YouTube video-sharing platform and the user experience using VR HMD (Oculus Quest) and tablet (iPad). The 360-panorama video content uploaded to YouTube can be easily accessed through an application or website on various devices. Multiple users can experience the design alternatives without time or spatial constraints by accessing the video link, and comment or like functions can be employed to collect user opinions and preferences.

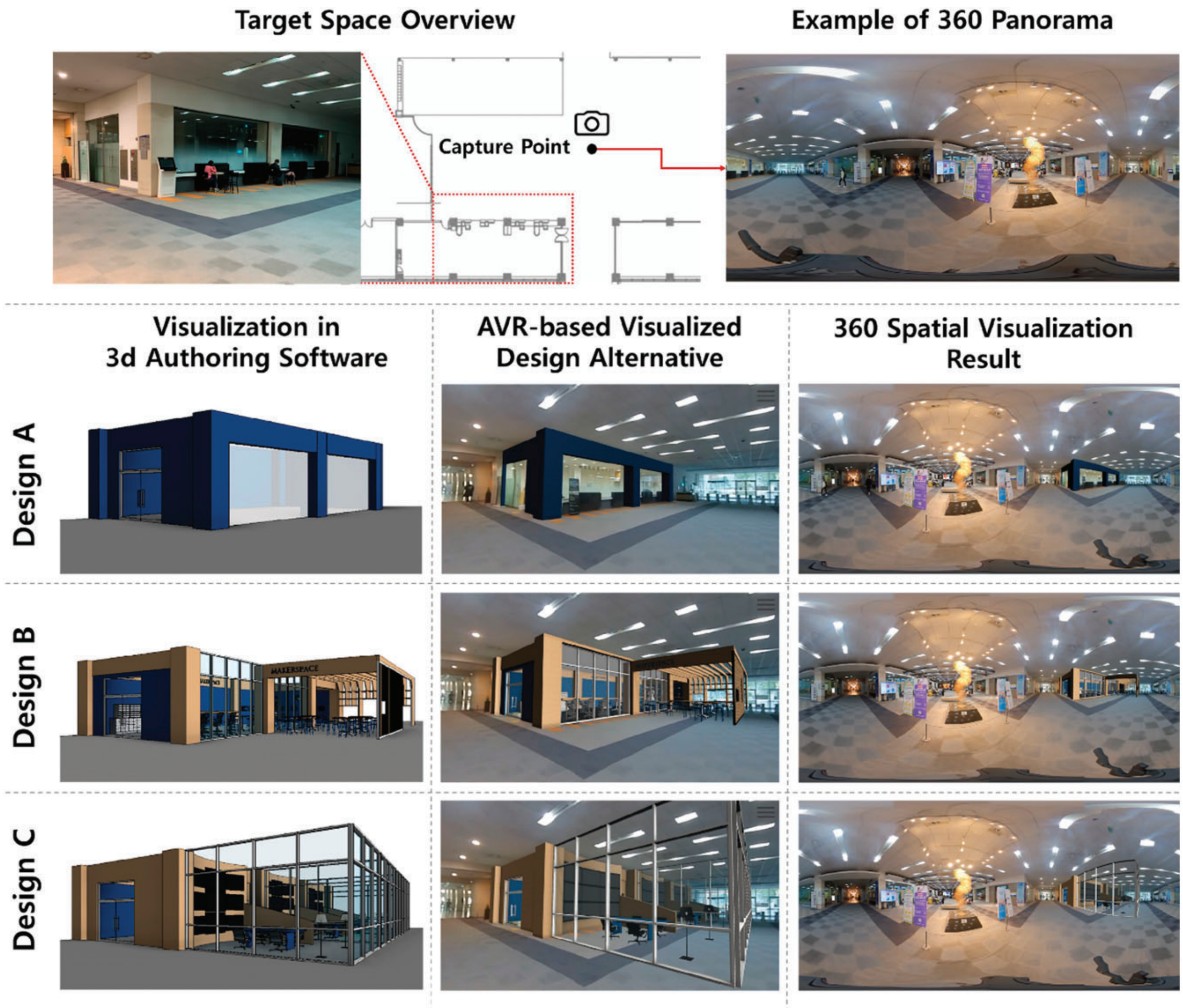

Figure 9: Target space overview and examples of the 360 spatial visualization results.

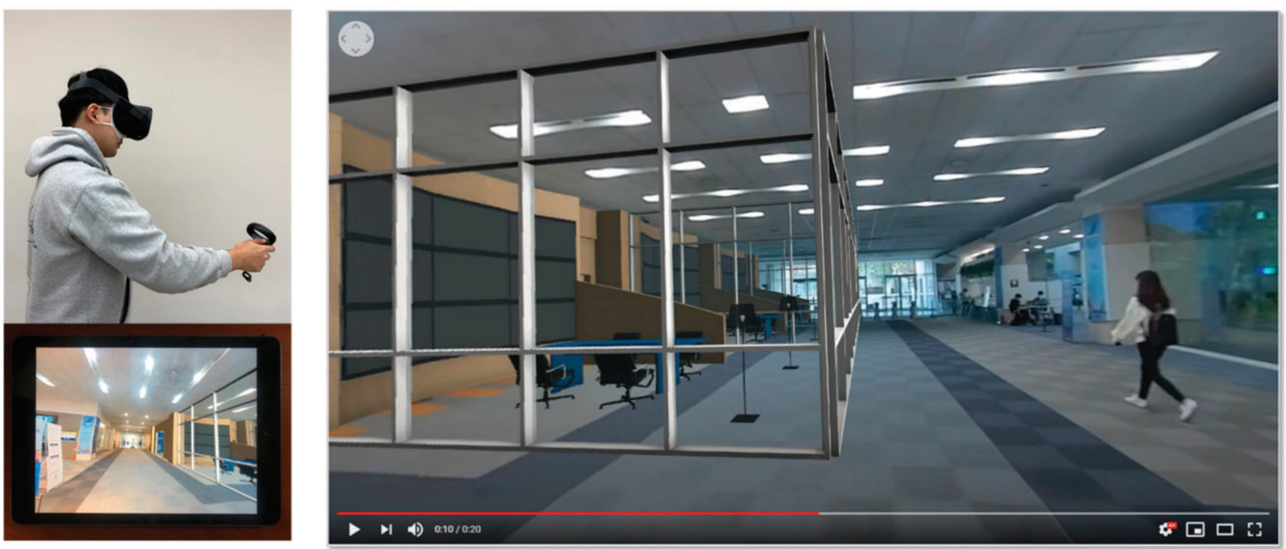

Figure 10: Example of user experience of video using VR HMD and tablet (left-hand panel) and uploaded 360 spatial visualizations in a video-sharing platform (right-hand panel).

5. Discussion

AR devices are rapidly developing to provide users with an immersive experience, but currently, their hardware performance, such as the degree of the FoV or the computing power, is limited in delivering such an experience. The AVR-based approach discussed in this paper can leverage the benefits of both the realism of AR and the immersion of VR. The contributions of the AVR and 360 spatial visualization-based approaches described in this paper are as follows:

(i) Demonstrating the possibility of the AVR-based approach, which integrates the advantages of VR and AR to support design decisions. The 360 panorama data-based design visualization provides a sense of realism, and devices such as the VR HMD can be used for an immersive experience.

(ii) Prototyping 360 spatial visualization software to demonstrate the AVR approach. The prototype software authors a 360 panorama video, which is easily accessible to multiple users and provides design information off-site as if the user were on-site.

We focus on the 360 spatial visualization of design, which uses panoramic data captured at one point among various AVR application scenarios. The resulting 360 panorama video format can be experienced by multiple users simultaneously. In the future, a real-time collaborative environment could be proposed where multiple designs are shared from a distance using high-speed network streaming.

Although AVR-based 360 spatial visualization can be used to visualize and support design decisions, it has a limitation in that it does not support user interactions for design review, such as adding design objects or changing the texture. In addition, we only implemented a superimposing design model on 360 panorama data without spatial depth data. In AR, the occlusion function that recognizes the spatial depth between the real world and digital data is realistically used for visualization. It could be important to use the spatial depth data for a more realistic and immersive experience. The methods for acquiring depth data are also expanding. Recently, handheld devices, such as tablets and smartphones equipped with a lidar sensor, have been developed. Moreover, a deep learning-based approach that predicts the spatial depth from a single image could be another applicable technique, as well as other type of advances in design computing researches and further developments (Sanguinetti *et al.*, 2012; Song *et al.*, 2020).

6. Conclusions

In this paper, we discuss the AVR-based design visualization process that integrates both the immersion of VR and the realism of AR to support design decisions for interior design alternatives. Based on this process, we implemented a 360 spatial visualization software prototype, which visualizes design alternatives in the form of a 360 panorama video. We demonstrated the software using the remodeling design alternatives for the university library lobby.

By sharing the authored 360 panorama video, we expect that multiple users can experience interior design alternatives with a sense of realism and immersion through a non-face-to-face method, without actually visiting the space. We also expect that the AVR-based approach enables users to understand the surrounding contextual information, such as human movement, adjacent space use, and other information. The applicability of this approach rests on supporting design decisions by identifying the design preferences of end users. A future study aims to investigate the empirical effects of AVR on user engagement and design decision-making using standardized questionnaires. Another future study will develop an advancing AVR system that allows for realistic interactions between design alternatives and 360 panorama data relying on depth computation. We also note that the Unity-based software implementation is for demo purposes only, and our future study aims to develop an accessible online app for actual and empirical uses of this implementation.

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