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A Comparative Review of Construction VR Applications: Functionality, Simulation, and Collaboration

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ABSTRACT

While the gaming and entertainment market was lit up by the arrival of Virtual Reality (VR) in 2016, it has brought significant consideration of immersive visualization to the architecture and construction industry since then. The capabilities of VR in architecture and construction today have reached beyond just walking into and seeing the built environment. It has become mature enough and been kept more consistent to be applied in real-world construction projects. In order to provide the architecture and construction industry more comprehensive and up-to-date knowledge of using VR applications, this paper presents a thorough comparative review of current computer-based construction applications that offer VR capabilities. Eight applications were identified through a literature review and Internet search, and their VR capabilities in terms of functionality, simulation, and collaboration features were compared and evaluated. Six of them were tested with three different types of VR headsets, namely Oculus Rift with Touch controllers, HTC Vive, and Windows Mixed Reality headset. The advantages and disadvantages of each VR headset were discussed, and recommendations were given on the selection of appropriate construction VR applications based on the most desired features. This paper provides the most current first-hand information to architecture and construction firms who are interested in applying the VR technology in their projects.

Keywords: *Virtual Reality, Construction, Application, Comparison.*

INTRODUCTION

The Virtual Reality (VR) boom due to the arrival of Oculus Rift in 2016 has brought significant consideration of its uses in the architecture and construction industry despite its main focus on the gaming and entertainment market. As primarily a visualization tool, one of the first advantages VR offers the architecture and construction industry is the ability to personally experience the built environment in an immersive manner that no other existing visualization tools can ever match. Architects and construction professionals have soon realized that VR is able to offer more than just letting people walk into and see the built environment, and since then the capabilities of construction VR applications have developed tremendously.

After two years of development, these capabilities have become mature enough and been kept more consistent to be applied in real-world construction projects. Therefore, there is an urgent need to identify what construction VR applications are available, evaluate how their VR capabilities compare to each other, and assess the benefits these construction VR applications can bring to the industry.

Through a literature review, it was found that only a handful of construction VR applications were identified and reviewed at their early stage, which likely did not cover their entire capabilities after being fully developed. This paper aims to present a thorough comparative review of the functionality, simulation, and collaboration features of current construction VR applications in order to provide the architecture and construction industry more comprehensive and up-to-date knowledge of using VR applications in real-world construction projects. This study focused on computer-based VR applications as these applications are able to work directly with Building Information Modelling (BIM) programs, convert BIM models into the VR mode in real time, and display BIM models through a VR headset with the same computer. As a result, mobile-based construction VR applications are not covered in this paper. Eight construction applications with VR capabilities were identified and six of them were tested with three different VR headsets in this study. Through the comparative review of their functionality, simulation, and collaboration features, recommendations were given on how architecture and construction firms at different levels of interest in VR can apply these applications more effectively in their projects.

BACKGROUND

VR Hardware

Since the release of the consumer version of Oculus Rift in early 2016, there have been three different types of computer-based VR headsets available: Oculus Rift, HTC Vive, and Windows Mixed Reality (MR) headset. Oculus Rift was released the earliest among the three with a headset, a desktop-mounted wired sensor, and an Xbox controller. The single sensor setup only tracks head movement in six degrees of freedom (direction and orientation change in three-dimensional space). It does not support room-size tracking and does not track hand movement. Oculus Touch motion-tracked controllers were released later at the end of 2016 packaged with an additional sensor to support hand movement tracking and room-size tracking. A standard setup of Oculus Rift would be the headset, two Touch controllers, and two desktop sensors, with the Xbox controller as alternative input if needed.

HTC Vive was released soon after Oculus Rift with a headset, two wall-mounted wireless sensors, and two motion-tracked controllers. This setup is almost identical to Oculus Rift with Touch controllers except for that the wall-mounted sensors allow large movement area within the VR room. The specifications of both headsets are also identical with a resolution of 1080x1200 per eye and a field of view of 110 degrees.

Windows MR Headset, as a newcomer to the VR arena, was released almost one and half years later than the other two. Despite being named as an MR headset that runs the Microsoft Mixed Reality platform, it is actually a VR headset based on its functionality. It is manufactured by a variety of vendors under different names, such as Lenovo Explorer, Dell Visor, Samsung Odyssey, as well as Acer, HP, and ASUS, and all come with very similar specifications at a resolution of1440x1440 per eye (1440x1600 for Samsung Odyssey) and a field of view between 95 to 110 degrees. The two motion-tracked controllers for all Windows MR Headsets are based on the same design. The Windows MR headsets use inside-out tracking that detects the motion-tracked controllers as well as room boundaries with two cameras mounted on the front of the headset, and thus do not need any sensors for tracking.

Besides computer-based VR headsets, there are three other types of VR headsets that are outside of scope of this study, which are PlayStation VR, mobile-based VR, and standalone VR. PlayStation VR works only with Sony PlayStation 4 and is solely focused on the gaming market. Mobile-based VR usually requires uploading BIM models to a cloud server from a computer for VR processing before downloading to a Smartphone for viewing with a VR headset, such as Samsung Gear VR and Google Daydream View. Standalone VR works similarly to mobile-based VR, except for that it has integrated all smart phone components into the headset, including the processor, memory, storage, and battery. Such standalone VR includes Oculus Go, Lenovo Mirage Solo, and HTC Vive Focus. Similar to mobile-based VR, they are focused on the entertainment market.

Literature Review

Due to its ability in immersive visualization of BIM models, VR has been growing rapidly in the architecture and construction industry since the first modern VR headset, Oculus Rift Development Kit 1, was made available in 2013. Considered as one of the most exciting technologies to hit this industry in years, VR offers its user a sense of scale, depth, and spatial awareness that simply cannot be matched by any rendering pictures, walkthrough videos, or scale models (Corke, 2017). A fully immersive VR experience is able to fool a user’s brain to create a feeling of presence inside the 3D model and provide the freedom to explore how a proposed building will feel and function through inspecting the details, walking across rooms, and teleporting through doors (Corke, 2016). Due to the unique benefits that VR brings to the industry, research efforts have started to investigate its uses in various areas in architecture and construction. Froehlich and Azhar (2016) evaluated the use of Oculus Rift in construction safety training and jobsite management, while Petrova et al. (2017) evaluated such use in end-user involvement in building design. Dayan and Sasks (2017) investigated the enhancement of cognition using Oculus Rift in apartment customization. Ozcelik et al. (2017) and Carneiro and Becerik-Gerber (2017) studied the use of Oculus Rift in understanding occupant-system interactions related to thermal changes and lighting quality, respectively. Soman and Whyte (2017) and Lovreglio et al. (2017) developed a framework with VR visualization for real-time construction progress monitoring and earthquake evacuation, respectively. Asgari and Rahimian (2017) investigated different VR tracking devices for construction process optimization and defect prevention. All these recent research projects employed VR devices as an effective tool for improving the interaction between human experiences and building environments.

Besides research efforts, software developers have also dedicated to maximizing the potential of VR in architecture and construction. Corke (2016) introduced several software developers that have created VR environments for architecture and construction projects, including TruVision, UE4Arch, IrisVR, ArqVR, by using 3D game engines such as Unreal Engine, Unity, Stingray, and CRYENGINE. Corke (2017) further tested three VR applications with HTC Vive in early 2017, namely Autodesk Live (rebranded to Revit Live), IrisVR Prospect, and Enscape, to demonstrate the process from Revit to VR. These applications are able to convert everything in a Revit file into a VR environment, such as the model itself, including materials and lighting, as well as the site environment and sun settings, by simply pressing a few buttons without any game engine, and are thus well-suited for average BIM users. Since Corke's (2017) test was carried out at the early stage of VR in architecture and construction, many other applications with similar purposes were not identified and evaluated, and their capabilities and benefits were thus undetermined.

METHODOLOGY

Construction VR Applications

With two years of development, the capabilities of construction VR applications have become mature enough and been kept more consistent to be applied in real-world construction projects. Through a literature review and Internet search, eight computer-based applications were identified to offer VR capabilities for architecture and construction uses. Their developers, application names, and icons arelisted in Table 1.

Table1. *Evaluated computer-based VR applications for architecture and construction uses*

Developer	Autodesk	Enscape	Kalloc	Vizerra	SimLab	Vrban	IrisVR	Kubity
App name	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
VR use	Feature	Feature	Feature	Feature	Feature	Purpose	Purpose	Purpose
Tested	Y	Y			Y	Y	Y	Y

Autodesk Revit Live and Enscape offer similar rendering capabilities. Autodesk Revit Live is a cloud service that converts uploaded Revit models into a rendered real-time 3D scene that can be viewed in VR mode. It is not a different version of the well-known BIM modelling tool Revit but is rebranded from Autodesk Live to establish the recommended workflow from Revit to Revit Live.Enscape is a real-time 3D rendering tool that focuses on enhanced visualization of BIM models, and it supports such visualization in the VR mode.

Kalloc Fuzor and Vizerra Revizto are both a complete BIM platform that synchronizes with BIM modelling tools and provides comprehensive BIM design and analyses, including material and lighting editing, section cut and visibility control, weather and daylight simulation, clash management, distance measurement, multiuser collaboration, VR support, etc.

SimLab Composer is a 3D designing and modelling tool for architecture, interior design, and product design. It specializes in rendering, simulation, and animation, and offers VR capabilities to enhance its rendering and simulation features. Composer includes various editions that are made specifically for either architectural and interior design, mechanical design, rendering only, or VR visualization.

VrbanInsiteVR and IrisVR Prospect, by their names, are built solely for the purpose of VR uses, as indicated in Table 1. As a result, the program itself is merely used to manage uploaded VR projects and organize VR meetings, and all of their key features are provided through VR. InsiteVR uses a web application while Prospect needs to be installed to upload and manage VR projects. Kubity, another VR-purposed application, works very similar to Prospect except for that it offers fewer features.

All eight construction VR applications provide an add-on or plug-in for BIM modelling tools such as Autodesk Revit and Trimble SketchUp to allow model upload or VR conversion. In addition, many applications also provide mobile-based VR capabilities, including Fuzor, Composer, InsiteVR, IrisVR Scope, and Kubity.

Comparison Environment and Criteria

Six out of the eight identified construction VR applications were tested in this study due to the fact thatthe authors were not able to obtain access to Fuzor and Revizto. Nevertheless, information on these two applications in this paper was based on their website documentation and video demonstrations and is therefore as accurate as the other six applications. Each application was installed on three VR-ready computers with slightly different specifications. Oculus Rift and HTC Vive were connected to an individual desktop computer to accommodate their sensor setup while an Acer Windows MR headset was connected to a laptop computer to allow its sensor-free mobility.

Although the three VR headsets run on different software systems, e.g., Oculus Rift runs applications from Oculus Home, HTC Vive runs Steam applications through SteamVR, and Windows MR Headsets run Microsoft Store MR Applications through the Mixed Reality Portal in Windows 10, they all allow third-party VR applications. Particularly, Windows Mixed Reality for SteamVR, a Steam program, is needed for Windows MR Headsets to run third-party applications. The six construction VR applications were installed on each of the three computers to compare their compatibility with the three different types of VR headsets.

Each application was tested with its own sample project, which has usually been designed and optimized to support its full features. The navigation tools, functionality features for construction purposes, rendering and simulation effects, and multiuser collaboration support of each construction VR application were tested and compared in detail. In addition, the supported file formats as well as the ease of access were also evaluated between the eight construction VR applications.

RESULTS

Headset Support

Among the three different types of VR headsets, Oculus Rift and HTC Vive are supported by all eight construction VR applications. Composer however, does not support the Touch controllers, and the Xbox controller is needed when using Composer with Oculus Rift, which lacks hand movement tracking. Except for Revizto and Kubity, the rest six applications support Windows MR Headsets through Windows Mixed Reality for SteamVR. All VR applications also support the basic mouse and keyboard input. Table 2 summarizes the headset support of construction VR applications.

Table2. *Headset support of construction VR applications*

Hardware support	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Oculus Rift	Y	Y	Y	Y	Y	Y	Y	Y
Oculus Touch	Y	Y	Y	Y		Y	Y	Y
HTC Vive	Y	Y	Y	Y	Y	Y	Y	Y
Windows MR	Y	Y	Y		Y	Y	Y	
Mouse/Keyboard	Y	Y	Y	Y	Y	Y	Y	Y

Navigation

Navigation features allow the user to move around in the VR scene through different methods to personally experience the built environment. Navigation is the fundamental use of construction VR applications since the basic concept of adopting VR in the architecture and construction industry is to create an immersive experience. Typical navigation features in construction VR applications are summarized and compared in Table 3, which include adjusting user height, walking, teleporting, rotating, and scaling. Adjusting user height allows the VR user to change the height of sight at which the VR scene is being observed. All applications except Composer offer this feature. Walking within the VR scene is achieved by either pressing the joystick/touchpad on the controllers or walking physically within the sensor-tracked area. Walking through controllers is however not recommended because the user could easily experience motion sickness since it makes the brain think the user is walking while he/she is actually not. A better way to talk within the VR scene is to physically walk within the VR area established earlier by the user.

Table3. *Navigation features of construction VR applications*

Navigation features	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Adjust user height	Y	Y	Y	Y		Y	Y	Y
Walk with button	Y	Y	Y	Y	Y	Y	Y	Y
Walk physically	Y	Y	Y	Y	Y	Y	Y	Y
Teleport	Y	Y	Y	Y	Y	Y	Y	Y
Teleport to view	Y		Y	Y		Y	Y	
Rotate view	Y	Y	Y	Y	Y		Y	Y
Rotate miniature	Y	Y	Y	Y		Y	Y	Y
Scale miniature	Y		Y	Y		Y	Y	

All three VR systems are able to display a virtual boundary of the VR area to prevent the user from colliding with objects in the physical space. All eight applications perform the walking function very similarly. To make movement easier, teleportation allows the VR user to move to any location instantly in the VR scene without having to walk. This is achieved by displaying a laser beam or projectile from a controller to indicate the location to teleport to, as demonstrated in Fig. 1. It is noticed that the screenshot is distorted due to the mirroring of round lens of the VR headstone rectangular computer display. All applications offer the same teleportation feature. Some applications also allow the user to save a view or location in the VR scene to teleport back to at any time, including Revit Live, Fuzor, Revizto, InsiteVR, and Prospect. The view in the VR scene is controlled by the position of the headset. Most applications allow view rotation through the controllers without having to physically rotate head position.

Figure1. *Teleportation projectile indicator in Revit Live with HTC Vive*

All applications except Composer have the ability to display a building model at a miniature scale to allow observation of the model from a bird view as compared to the immersive view, as illustrated in Fig. 2. In addition to physically walking around to observe the miniature model from different directions, most applications allow the VR user to rotate the miniature with the controllers. Some applications also allow custom scaling of the miniature to provide better details at a closer distance from the bird view.

Figure2. *Miniature scale of a building model in Prospect with Oculus Rift*

Functionality

While the navigation features are more or less in common among the eight VR applications, their construction-related functionality makes them unique from one another. Depending on their built purpose, some applications offer a variety of features that can add great value to design and construction, while others may only provide minimum to none.

Typical basic construction-related functionality features include measurement tool, mark-up tool, snapshot tool, and saving views. More advanced utility features that are usually found on the computer platform include turning layers on/off, inspecting object information, and performing section cut. Table 4 details the construction-related capabilities that each VR application offers.

Table4. *Functionality features of construction VR applications*

Functionality features	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Measurement	Y		Y	Y		Y	Y	
Markup			Y	Y		Y	Y	
Snapshot		Y				Y	Y	
Save view	Y		Y	Y		Y	Y	
Layer on/off			Y	Y			Y	
Object information	Y		Y	Y			Y	
Section cut			Y	Y			Y	

The measurement tool allows the user to measure the distance between two points or the floor to ceiling height in the VR scene. This tool is helpful in checking the dimensions and relative positions of building components in the design. Fig. 3 demonstrates measuring the length of a TV stand in Prospect. The markup tool allows the user to add annotations and comments to building components in the VR scene for identified issues during a virtual inspection. Fig. 4 illustrates the markup of a column in InsiteVR. The snapshot tool works conveniently with the measurement and markup tools in that it allows the user to take and store pictures of the measured distance or marked area for further discussion and future reference. InsiteVR and Prospect offer all these three tools while Revit Live can take measurements, Enscape can take snapshots, and Fuzor and Revizto can do both. In addition to saving snapshots, some applications allow the user to revisit saved views or locations for direct teleportation, as described in the navigation features, which can assist the inspection of design changes in the marked areas. Turning layers on/off provides the ability to change the visibility of building components of the same type or being placed on the same layer when the BIM model was created. It allows the VR user to hide certain objects to better observe the built environment in either the immersive view or the bird view. It is very typical to hide the architectural model to observe the structural framing and mechanical systems. Fig. 5 presents a miniature model in Prospect with the layers of roof, exterior walls, and glass panels turned off to observe the layout of rooms and interior furniture. Inspecting object information allows the user to select a building component in the VR scene and inspect its property information, such as category, type, level, height, area, volume, material, etc., that belongs to the object when created withthe BIM modeling program.

Figure3. *Measurement tool in Prospect with Oculus Rift*

Figure4. *Markup tool in InsiteVR with Oculus Rift*

The sectioning tool allows the user creates section planes in the miniature model that cut through the building at custom positions and angles to better inspect the interiors. Fig. 6 shows a miniature model in Prospect with a vertical section cut performed by the right Touch controller. Fuzor, Revizto, and Prospect provide these three advanced functionality features, while Revit Live is able todisplay object information. In addition, it has been noted that although Fuzor and Reviztoare both a complete BIM platform, Fuzor supports full control in the VR mode while Revizto offers VR capabilities mostly as a viewing tool, which means these features must be manipulated by a computer mouse instead of the VR controllers.

Figure5. *A miniature model with various layers turned off in Prospect with Oculus Rift*

Figure6. *A miniature model with a vertical section cut in Prospect with Oculus Rift*

Simulation

Similar to the functionality features, the eight construction VR applications offer various combinations of simulation and animation features depending on their built purpose. The rendering and simulation effects make these applications stand out as excellent BIM visualization tools for demonstration and marketing purposes.

Table5. *Simulation features of construction VR applications*

Simulation features	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Realistic rendering	Y	Y	Y		Y			
Object simulation	Y	Y	Y		Y			
Daylight simulation	Y	Y	Y	Y	Y	Y	Y	Y
Lighting simulation	Y	Y	Y	Y	Y	Y	Y	Y
Change material			Y	Y	Y			
Move object			Y		Y			
Object interaction	Y		Y		Y			

Typical simulation features include simulating object effects, daylight changes, and lighting effects, as well as the ability to change object materials, move and interact with objects. Table 5 details the simulation capabilities that each construction VR application offers.

The eight applications render VR scenes with different image quality. The VR scenes rendered by Revit Live, Enscape, Fuzor, and Composer look more realistic than the other applications due to the rendering engine and materials used, and consequently demand more computer resources. The same four applications also simulate dynamic object effects, which allow the user to observe the natural movement of certain objects in the VR scene, such as burning flames, water waves and reflections, smoke, swinging leaves, spinning fans, television contents, etc. These dynamic effects consume much higher computer resources since they are constantly changing. Fig. 7 shows the movement of water waves and their reflections in a pool in Revit Live.

Figure7. *Simulation of water waves and reflections in Revit Live with HTC Vive*

Daylight simulation allows the VR user to change the current time in a day to adjust the sun position and observe the effects of daylight change on the built environment in the VR scene. Fig. 8 illustrates changing the current time to observe the movement of light post shadows in Prospect.

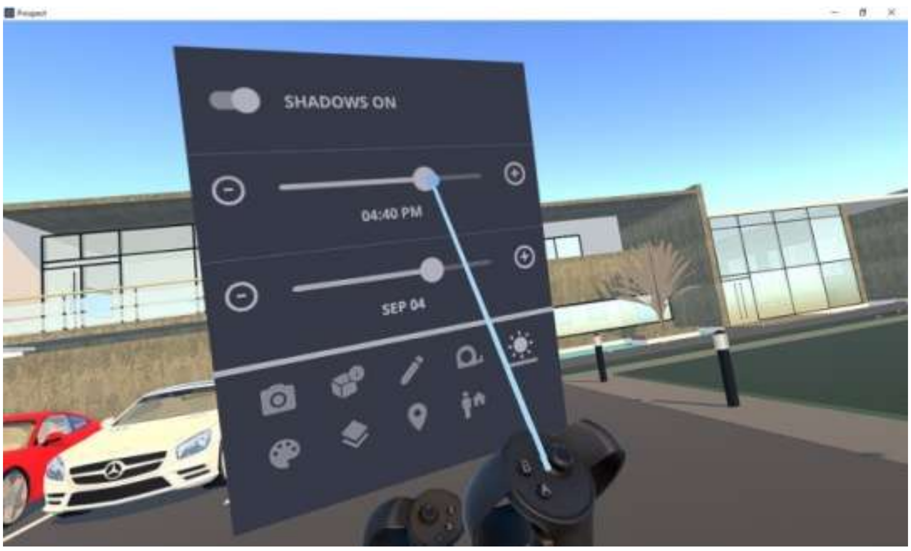

Figure8. *Simulation daylight change and shadow movement in Prospect with Oculus Rift*

Lighting simulation allows the user to observe and adjust the lighting effects in the VR scene when artificial lighting is added in the BIM model. Lighting effects can be observed when the time of day is set to night and artificial lighting becomes the main lighting source. Fig. 9 presents the effects of various interior lighting of a building at night time in Enscape. All eight applications support both daylight and lighting simulation as the basic simulation features.

Figure9. *Simulation of artificiallighting at night time in Enscape with Oculus Rift*

Some simulation-focused applications have further capabilities to interact with objects. Fuzor, Revizto, and Composer allow the user to apply different materials or colors to certain objects to observe alternative design options. Fig. 10 shows the different color selections of kitchen cabinets in Composer. Fuzor and Composer also allow the user to pick up certain objects with controllers and relocate them for alternative furniture layouts, and support user interaction with building components that are meant to be operated by the occupants, such as doors, windows, cabinets and closets, light switches, appliances, etc. Revit Live allows doors to open automatically when the user approaches them in the VR scene. Fig. 11 demonstrates using the Vive controllers to open an oven in Composer.

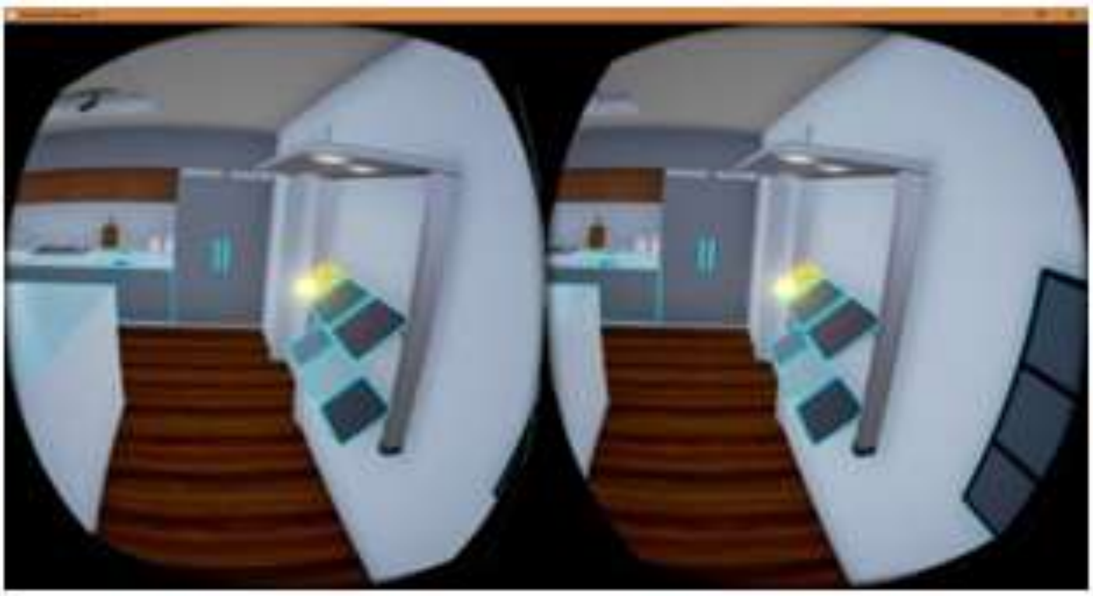

Figure10. *Changing object color in Composer with Oculus Rift and Xbox controller*

Figure11. *Opening an oven in Composer with HTC Vive*

Collaboration

Multiuser collaboration has become an increasingly important feature for construction VR applications as the nature of construction projects requires a project team to be able to see and communicate within the same VR scene. Multiuser collaboration is offered by Fuzor, Revizto, InsiteVR, and Prospect as a premium feature, as presented in Table 6. The collaboration feature allows multiple VR users, each wearing his/her own VR headset, to view the same built environment at the same time. All participants can walk freely in the shared virtual environment and observe the presence of one another in the VR scene. A headset or avatar model with the user's name is displayed to represent the positions of each participant in the scene. In addition, participants can present a laser dotfrom their avatar models with the controllers to guide the project team on the same building component during a team discussion. Some applications also allow non-VR users to join a VR collaboration meeting through computer programs and indicate their presence in the VR scene differently. Fig. 12demonstrates the collaboration feature in InsiteVR, where aVive user and a Rift user are able to see each other's virtual position through the movement of each other's name, headset, and controllers in the VR scene.

Table6. *Collaboration feature of construction VR applications*

Collaboration feature	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Collaboration			Y	Y		Y	Y	

Figure12. *Collaboration between two users in InsiteVR with HTC Vive and Oculus Rift*

Compatibility

The eight VR applications support different types of file formats, as detailed in Table 7. As the most popular BIM modeling program, Revit files are supported by all eight constructionVR applications. Except for Revit Live, the rest seven applications support SketchUp files, although Trimble does not have its own computer-based VR application like Autodesk. Some commonly supported file formats also include Rhino, FBX, 3ds Max, Navisworks, and ArchiCAD, each supported by three to five applications. Other file formats supported by one to two applications include AutoCAD, SolidWorks, Solid Edge, and Grasshopper.

Table7. *Compatibility of construction VR applications*

Supported file formats	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Revit	Y	Y	Y	Y	Y	Y	Y	Y
SketchUp		Y	Y	Y	Y	Y	Y	Y
Rhino		Y	Y	Y	Y		Y	
FBX			Y	Y	Y	Y	Y	
3ds Max			Y		Y	Y	Y	
Navisworks			Y	Y		Y		
ArchiCAD			Y	Y		Y		
AutoCAD				Y	Y			
SolidWorks					Y			
Solid Edge					Y			
Grasshopper							Y	

Ease of Access

Due to the constantly changing license cost of software applications, this study only reviews and compares the access types of licenses of the eight construction VR applications, as detailed in Table 8. With the popularity of the Software as a Service (SaaS) distribution method, all eight applications offer yearly subscription licenses while some also provide a monthly subscription option. The licenses can be subscribed for either individual standalone computers or floating network uses. Composer is the only application that still offers perpetual licenses, which reduce the cost for long-term use, but lack the support of major upgrades.

Fuzor, Revizto, Composer, InsiteVR, and Prospect offer tiered subscription or perpetual licenses to allow more flexibility when purchasing license. The license cost is typically structured into three to five tiers based on the features or number of projects supported for each tier. Low-tier licenses may only support VR navigation with basic functionality features in a limited number of projects, while high-tier licenses allow full functionality with simulation or collaboration features in unlimited number of projects. Several construction VR applications provide free licenses for a trial period, a basic tier, a viewer-only tool, or educational uses.

Table8. *Ease of access of construction VR applications*

Access types	Revit Live	Enscape	Fuzor	Revizto	Composer	InsiteVR	Prospect	Kubity
Subscription license								
Standalone	Y	Y	Y		Y		Y	Y
Network		Y	Y	Y		Y	Y	
Monthly	Y	Y	Y				Y	
Yearly	Y	Y	Y	Y	Y	Y	Y	Y
Perpetual license								
Standalone					Y			
Network					Y			
Tiered license								
By feature			Y		Y		Y	
By #of projects				Y		Y		
Free license								
Trial	Y	Y			Y	Y	Y	
Basic								Y
VR viewer	Y		Y		Y			
Educational		Y			Y		Y	

A trial period usually lasts between 14 to 45 days with full features for the user to evaluate the capabilities of the application before making a decision of purchase. Kubity offers a free basic-tier license that allows VR conversion from a BIM modeling program for one project. Prospect used to offer a similar free basic-tier license during their development stage. Revit Live and Fuzorare able togenerate executable files for free VR viewing while Composer provides a free viewer to explore the VR scenes created by Composer.

These free VR viewers do not have the ability to convert BIM models into the VR mode. In addition, Enscape, Composer, and Prospect also provide free educational licenses for educators and students.

Discussion And Recommendations

VR Hardware

The three different types of computer-based VR headsets provide a very similar VR experience in general, although there are a few specific advantages and disadvantages of each headset. Oculus Rift has a lightweight design which allows a longer duration of use without much weight pressure on the user's head. It however leaks light noticeably at the nose position which could affect the immersive experience. Due to the setup of two desktop-mounted sensors, Oculus Rift requires at least three USB ports. In addition, the sensors will lose tracking of the Touch controllers whenever the user turns backwards and stands in between the sensors and the controllers. The VR movement area is also limited to the space right in front of the sensors. An additional two sensors can be added to the system for better tracking and larger movement area, which at the same time requires two more USB ports. A separate wireless adapter, TPCast, is available for Oculus Rift to eliminate the cables between the headset and computer. HTC Vive is heavier than Oculus Rift due to its bulkier design but has more room within the headset to better accommodate prescription lenses. Its two wall-mounted sensors allow a larger area of movement and seldom lose tracking of the controllers. The headset has an integrated front-facing camera which, when turned on, allows the VR user to observe the physical environment as a small window in the VR scene.HTC Vive is supported by wireless adapters from both TPCast and HTC to eliminate the cables from the headset to the computer. All Windows MR Headsets, except for Samsung Odyssey, have a different design than the Oculus Rift and HTC Vive in that the headset can be flipped up without removing the headband to allow the VR user to temporarily see the physical environment. Its inside-out tracking approach eliminates the need of setting up the sensors but requires the controllers to stay in sight of the headset, otherwise it will lose tracking of the controllers just like Oculus Rift. The no-sensor design also gives more mobility to Windows MR headsets to be used between different computers.

Construction VR Applications

The eight construction VR applications offer a great variety of choices for architecture and construction firms at different levels of interest in applying VR in their projects. For entry level VR explorers, the free basic-tier license of Kubity provides a no-cost option for VR converting and viewing. The low-tier licenses of Composer, InsiteVR, Prospect, as well as Enscape, also provide more than enough features for a basic immersive VR experience. When project review and analysis is desired in the VR mode, Prospect meets the needs with its multi-tier licenses that cover from basic functionality features to team collaboration. Fuzor and Revizto also provide most functionality and collaboration features but without any trial period. When VR simulation is prioritized over functionality, Revit Live, Enscape, Fuzor, and Composer become the top choices. While all of them render VR scenes with realistic materials, Fuzor and Composer allow changing object materials and moving objects with extra modeling efforts. When team collaboration in the VR mode is more valued, Fuzor, Revizto, InsiteVR, and Prospect can handle multiuser VR meetings seamlessly. In addition to the various VR capabilities compared in this study, several applications also provide many other BIM-related features that architecture and construction firms can take advantage of. Revit Live specializes rendering Revit projects in the cloud while Enscapedoes it in real-time for both Revit and SketchUp projects. Fuzor and Revizto is a complete platform for BIM design and analyses while Composer is a 3D designing and modeling tool with powerful rendering, animation, and file-converting capabilities. Furthermore, if specific file formats have been used in design and modeling, such as Rhino, ArchiCAD, or 3ds Max, the construction VR application must be carefully selected according to Table 7.

CONCLUSIONS

While BIM benefits the delivery of construction projects by providing greater efficiencies at all stages of its lifecycle, VR offers the possibility of exploring the human elements of architecture, the form, space and aesthetics of buildings, through an immersive experience (Corke, 2016). Although not widespread yet, VR has shown extensive benefits to bring to the architecture and construction industry, from functional and aesthetic evaluation of projects to daylight and lighting studies as well as client collaboration and communication (Corke, 2017). In order to provide the architecture and construction industry more comprehensive and up-to-date knowledge of using VR applications in real-world construction projects, this paper presents a thorough comparative review of current computer-based construction applications that offer VR capabilities. Eight applications were identified through a literature review and Internet search, and their VR capabilities in terms of functionality, simulation, and collaboration features were compared and evaluated. Six of them were tested with three different types of VR headsets, namely Oculus Rift with Touch controllers, HTC Vive, and Windows MR Headset. The eight construction VR applications offer a wide variety of options for architecture and construction firms at different levels of interest in applying VR in their projects, from just exploring the immersive VR experience to full integration of project review, analysis, simulation, and collaboration. This paper provides the most current first-hand information to architecture and construction firms who are interested in applying the VR technology in their projects.

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