Abstract

Virtual Reality (VR) and the development of Virtual Environments (VEs) can make a significant impact on how construction project stakeholders can perceive and successfully complete their projects. VR techniques have the potential to enhance the efficiency and effectiveness of all stages of a project, from initial conceptual design through detailed design, planning and preparation, to construction completion. The ability to review the design and rehearse the construction of the facility in a 3D interactive and immersive environment can increase the understanding of the design intent, improve the constructability of the project, and minimize changes and abortive work that can be detected prior to the start of construction. Unlimited virtual walkthroughs of the facility can be performed to allow for experiencing, in near-reality sense, what to expect when construction is complete.

Various efforts in the industry and academia are underway to explore these possible benefits of VR in construction. This paper provides an overview of recent examples of successful adoption of VR technology as applications in construction. The paper also provides an overview of what Virtual Reality (VR) is, and discusses some of the hardware and software that can be used for VR applications.

Keywords: virtual reality, virtual environments, immersive, interactive, design, construction planning, visualization, CAVE, 3D modeling

1 What is Virtual Reality (VR)?

During the last two decades, the word *virtual* became one of the most exposed words in the English language [1]. The Webster dictionary defines it as “being such practical or in effect, although not in actual fact or name.” What we refer to as reality is based upon something we call the external physical world [2]. Therefore, a virtual reality seems to suggest a reality that is believable, and yet does not physically exist. Isdale [3] indicated that the term virtual reality (VR) is also interpreted by many different people with many meanings. To some people, VR is a specific collection of technologies and others stretch the term to include conventional books, motion pictures, radio, etc. - any medium that can present an environment that draws the receiver into its world.

In this paper, the term VR is restricted to being computer-mediated systems. This involves the use of computers to create and visualize 3D scenes supported by auditory or other sensual outputs, with which one can navigate through and interact. Navigation includes the ability to move around and explore features of the 3D scene, whilst the interaction implies the ability to select and manipulate objects in the scene. Interaction with the virtual world, at least with near real time control of its 3D scenes, is a critical test for a virtual reality.

Various definitions of virtual reality have been given by many researchers and practitioners. VR has been defined as a way for humans to visualize, manipulate and interact with computers and extremely complex data [4]. Barfield and Furness [5] described VR as “the representation of a computer model or database, which can be interactively experienced and manipulated by the virtual environment participant(s)”. Boman [6] characterizes VR as interactive, virtual image displays enhanced by special processing and by non-visual display modalities, such as auditory, tactile (touch), and haptic (force), to convince users that they are immersed in a synthetic space.

Halfawy *et al.* [7] classified VR as computer generated models of real environments in which users can visualize, navigate through, and interact with these models in an intuitive way. Sherman and Craig [8] defined virtual reality as a medium composed of highly interactive computer simulations that senses the user position, and replaces and augments the feedback of one or more senses - giving the feeling of being immersed or being present in the simulation.

Since the early 90’s, VR has matured considerably, and has begun to offer many powerful solutions to very difficult problems. New hardware platforms coupled with new complex graphics cards capable of generating high-end computer images have appeared. Other devices that provide tactile (touch) and haptic (force) images to complete the sense of illusion have been greatly improved. New more flexible and powerful commercial software systems geared towards generating real time virtual environments have also become available, with better features and capabilities. VR is no longer a technology looking for applications, but rather, it is a solution to many problems that involve real-time visualization of complex data.

Simultaneous with these developments, the term 'Virtual Reality' has been gradually ignored by some in preference for the term 'Virtual Environments' (VE). The use of the VE term avoids any possible implication that there is any ambition to remodel the universe [2]. Other terms that have been used include visually coupled systems, synthetic environments, cyberspace, artificial reality, virtual presence, and simulator technology. For the purpose of this paper, the terms virtual reality (VR) and virtual environments (VE) will be used interchangeably.

The following sections of the paper present a general overview of the different categories of VR, the current hardware and software technologies used for VR implementations, and provide a summary of current applications of VR in construction. The intention here is not to provide an exhaustive list or a complete review, but rather provide some example representations of what is available to make the reader aware of current technology and applications of VR in construction, and point the reader in the direction of more detailed references.

2 Types of VR Systems

As noted above, there is still a debate about what constitutes "virtual reality." Thus, there are many different types of systems that have been called VR. This section explores some of those categories of systems. The differences between these categories are due to several factors, including display hardware, graphics rendering algorithms, level of user involvement, and level of integration with the physical world.

2.1 Immersive VR

The most common popular image of VR is that of an *immersive* VR system – typically a user wearing a head-mounted display (HMD) or standing inside a spatially immersive display (SID). The concept of *immersion* is that the virtual environment surrounds the user, at least partially. Immersion is not a binary quantity – there are various levels of immersion. For example, a standard CAVE (section 3.1.1.2) has screens on four of the six sides of a cube; the user is only partially surrounded by the display.

A related, but separate concept is *presence* – the subjective feeling of "being there." For a user experiencing high levels of presence, the virtual world replaces the physical world as his "reality" [9]. An immersive VR system may produce higher levels of presence, but presence may also be achieved in non-immersive systems, or even in non-VR systems (e.g. a reader may become so engrossed in a novel that she feels present in the "world" of the book).

Immersive VR systems also generally use 3D interaction techniques based on whole-body input. In other words, to see what is to my left, I turn my head/body to the left; to move forward I take a step forward; to grab an object I reach out my hand and grasp the object with my fingers. These natural techniques may also be enhanced to allow for greater efficiency or usability. For example, the user might be given a virtual arm that can reach much further than his physical arm [10]. All of these techniques require the use of a tracking system.

2.2 Desktop VR

Non-immersive VR systems normally run on standard desktop computer workstations, thus the term "desktop VR." Desktop VR systems use the same 3D computer graphics as immersive VR systems, but there are two key differences. First, the display of the virtual environment does not surround the user – it is seen only on a single screen in front of the user. Second, the user typically navigates through and interacts with the environment using traditional desktop input devices such as a mouse and keyboard (although specialized 3D input devices may also be used).

2.3 Fish Tank VR

It is possible to use a desktop computer combined with a head tracker (Figure 1) to provide a "window" into a small virtual world, so that users can obtain different views of the world using natural head motions. This has been called "fish tank VR" [11] because the effect is similar to looking into various parts of a fish tank by moving one's head relative to the tank. The head tracking provides motion parallax information to allow the user to more easily comprehend the depth of 3D objects in the scene. Often, stereo graphics are used to enhance the 3D depth; this requires stereo glasses.

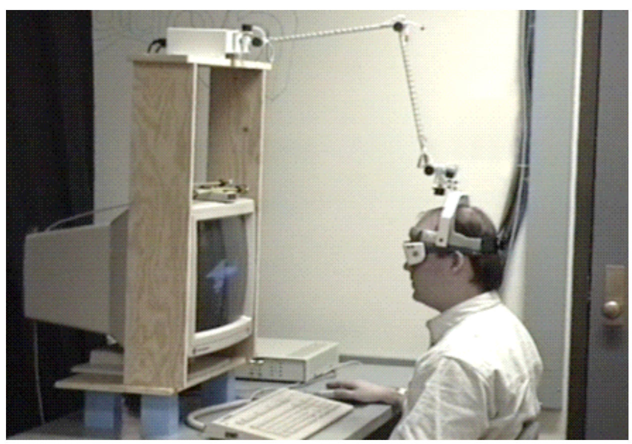

Figure 1: Fish tank VR setup using a mechanical head tracker

2.4 Image-based VR

Most VR systems display completely synthetic (computer-generated) virtual environments. The objects in these environments are made up of geometric primitives (usually triangles) along with colors and textures. However, it is also possible to display a realistic virtual world using only images. This is called *image-based rendering*, and its basic approach is to manipulate the pixels in images to produce the illusion of a 3D scene, rather than to build the 3D scene explicitly.

The simplest type of image-based VR is a panorama – a series of images taken with a camera at a single position pointed in multiple directions. These images can then be "stitched" together so that the seams are not visible, allowing the user to look in any direction and see the appropriate part of the scene. Apple's QuickTime VR is one of the most common types of panoramic VR. Of course, the limitation of panoramas is that the view is only correct when the viewpoint is at the exact position from which the images were taken. Thus, researchers have been studying the more general image-based rendering problem – that is, given a set of images taken from many positions and in many directions within an environment, how can we produce the correct perspective view from an arbitrary viewpoint in that environment [12, 13]. Image-based rendering has not yet made a large impact in VR, but it is clearly a way to increase the realism of virtual environments – an important consideration for the construction industry.

2.4 Highly Interactive VR

All VR applications involve *interaction*; that is, they allow the user some degree of control over what is happening. This is the characteristic that distinguishes VR from static 3D images or pre-computed 3D animations. Many VR systems, however, are simply walkthroughs or flythroughs – they display a static environment and allow the user to navigate (position and orient the viewpoint) through that environment. Highly interactive VR systems allow the user to perform other tasks in the VE, such as selection, manipulation, system control, and symbolic input.

Highly interactive VR systems can allow users to perform work in a VE that until now has only been available in 2D desktop systems (e.g. designing a building in a VE rather than in a CAD package). This takes VR from being simply a visualization tool to being a tool for producing real-world results. The key challenge for highly interactive VR is the design of usable and efficient interaction techniques and user interfaces.

2.5 Telepresence

Telepresence is related to VR, and involves interacting with real environments that are remote from the user [3]. Teleoperated systems are developed as a result of the need to interact with environments from a distance. This technology links remote sensors and actuators in the real world (teleoperators) with human operators who are at a remote location from that environment (Figure 2). This link provides the operator with a remote view of and limited control over the teleoperator's environment. This leads to a sense of telepresence. Current applications of telepresence involve the use of remotely operated vehicles (e.g. robots) to handle dangerous conditions (e.g. nuclear accident sites) or for deep sea and space exploration.

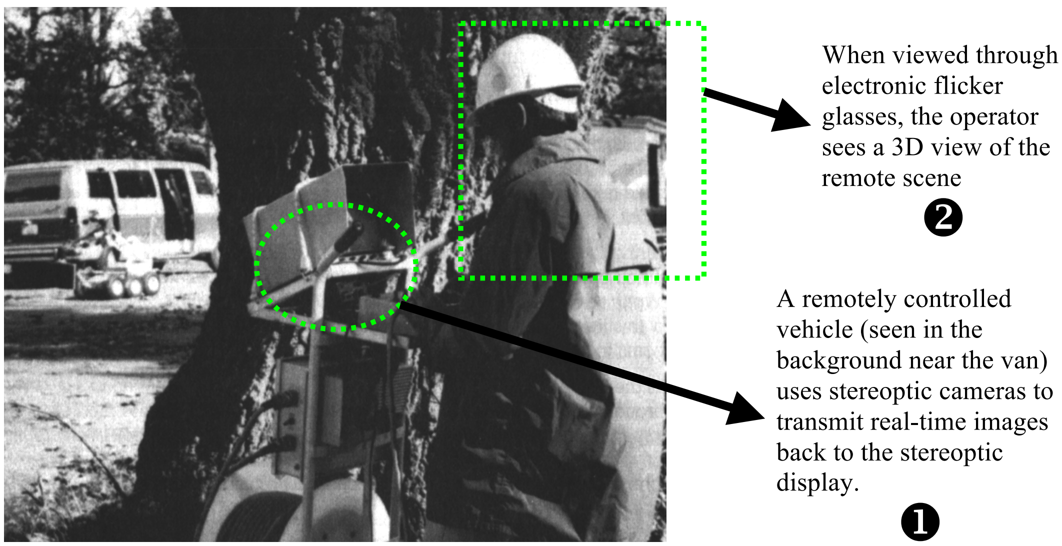

Figure 2: An example of a Telepresence system, adapted from [14]

2.6 Augmented/Mixed Reality

While VR provides a view of a completely virtual world, and telepresence a view of the physical world, augmented reality (AR) and mixed reality (MR) combine both virtual and physical environments into one. In AR systems, the user views the local real-world environment, but the system augments that view with virtual objects. For example, someone on a walking tour of a college campus might see labels that named all the buildings in his field of view (Figure 3) [15]. Augmented reality systems often use see-through head-mounted displays so that virtual and real images can be combined. Mixed reality (MR) refers to a whole continuum of systems that merge virtual and real environments, all the way from AR to mostly virtual environments that include some real-world objects.

Figure 3: Mobile augmented reality, adapted from [16]

3 VR Hardware

A wide range of hardware technologies is used to realize VR systems. We provide a high-level overview of some of the most important VR devices here, beginning with output devices, including visual, auditory, and haptic displays, and concluding with input devices, including discrete, continuous, and hybrid devices.

3.1 Output devices

The term display, in general, refers to a device that presents perceptual information. In VR systems, one goal is to involve as many of the user's senses as possible, so displays have been researched for almost all of the senses (visual, auditory, haptic (touch), olfactory (smell), and vestibular (motion) – we do not know of any research on a gustatory (taste) display). Here we present the three most common types of displays: visual, auditory, and haptic.

3.1.1 Visual Displays

The visual display is the one indispensable piece of hardware in a VR system, and often the visual display is the defining characteristic of the system as well. There are four general categories of VR visual displays.

3.1.1.1 Desktop Displays

The most common VR visual display is a simple desktop monitor, used for Desktop VR (section 2.2) or Fish Tank VR (section 2.3). Sometimes such displays are enhanced by using stereo graphics and stereo glasses to allow better depth perception, but for the most part they are identical to the displays used by all computer users.

3.1.1.2 Spatially Immersive Displays (SIDs)

To achieve immersive VR, a more complex visual display device is needed that allows the VE to appear to surround the user, or that fills much of the user's field of view with the computer graphics. One approach, called a spatially immersive display (SID) is to physically surround the user with the display(s). For example, the CAVE [17] uses 4-6 large projection screens in the shape of a cube into which the user can walk (Figure 4). Stereo graphics are projected onto the screens, so that the user sees nothing but the VE and their own body. The CAVE allows multiple viewers, unlike some other VR technologies, but normally only one viewer has the correct perspective view.

Another type of SID, called a dome or hemispherical display, uses only a single curved screen that wraps around the user to provide immersion. The Hemispherium™ (Figure 5) is an example of this type of display [18]. It uses a six-meter dome mounted vertically. The user sits in front of the dome so that the display fills his entire field of view. Smaller domes include the elumens VisionStation™. SIDs often provide excellent sensations of presence and high-resolution graphics, but can be quite costly, and are usually not fully-immersive (except in the case of the 6-sided CAVE).

3.1.1.3 Head-Mounted Displays (HMDs)

The head-mounted display (HMD) was the earliest VR display [19], and represents another method for achieving immersion. HMDs use two small LCD or CRT screens mounted inside a helmet worn on the user's head (Figure 6). The two screens can be controlled separately to allow for stereo graphics. The HMD blocks out the user's view of the physical world so that only the virtual world can be seen. When the HMD is combined with a head tracker, the user can view the VE in any direction simply by turning his head.

HMDs can be much less costly and more portable than SIDs, and provide complete physical immersion. However, they generally have a narrow field of view (30-90 degrees horizontal), a low display resolution (typically 640x480 or 800x600), and can be heavy and cumbersome.

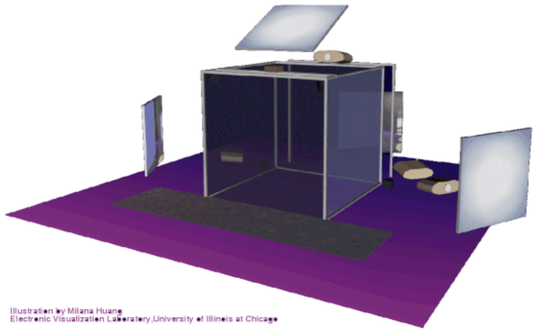

Figure 4: A CAVE system

Figure 5: User seated in the flight chair of the Hemispherium™

Figure 6: User wearing a head-mounted display

3.1.1.4 Workbenches and Walls

The final approach to providing some level of immersion and a wide field of view is to simply use a single, flat, very large display surface. Typically, this takes the form of a horizontal screen upon which the user looks down (a workbench) or a vertical screen mounted in front of the user (a wall). Most workbench and wall displays use rear-projected stereo graphics and stereo glasses for the user. Head tracking is also common, although not required. Some displays, such as Fakespace's Immersive Workbench (Figure 7) allow the screen to be rotated to produce a workbench configuration, a wall configuration, or anything in between. Workbenches and walls provide only limited immersion, but they do allow multiple users to share the display, and afford direct manipulation of the displayed data.

Figure 7: Immersive Workbench

3.1.2 Auditory Displays

In this case, the display hardware is not generally specific to VR – standard speakers or headphones can be used. The challenge is in creating sound that is realistic for a given environment. Many advanced VR systems use *spatial audio*, which presents auditory information that sounds as if its source is at a particular location in 3D space.

3.1.3 Haptic Displays

Haptics refers to all of the "skin senses" (force, pressure, texture, heat, pain, etc.). In VR systems, haptic devices allow the user to feel the virtual world. There are many different types of haptic displays that have been used in virtual environments. The most common type is a mechanical linkage device that displays force to the user at a single point, such as the Sensable Technologies Phantom device. This device allows users to probe virtual objects with a fingertip or stylus in order to feel the surface. Another type of device, called an exoskeleton (Figure 8, left), allows users to grasp virtual objects and feel the force on all five fingers. These two types can be combined to allow both grasping and probing (Figure 8, right). A third type of haptic display is the tactile display, which presents surface features, such as texture.

Near-field haptics [20] is a different approach to providing haptic sensations to the user, which uses real-world objects, called *props*, which match virtual objects in the VE. For example, a physical railing can be placed around the user in a virtual elevator, so that when she reaches out her hand to the virtual railing, she feels the physical railing at the same location [21].

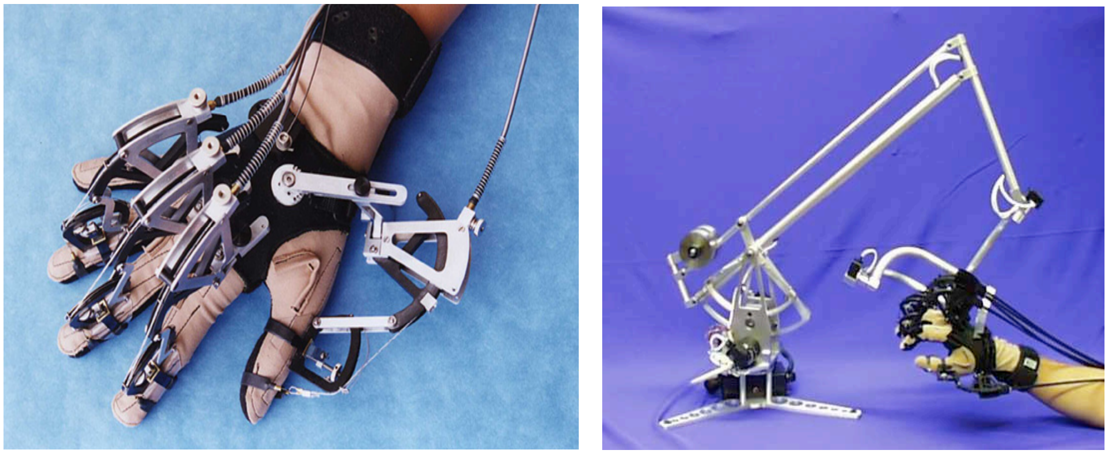

Figure 8: Exoskeleton (left) and combination exoskeleton and mechanical linkage (right) haptic devices from Virtual Technologies, Inc.

3.2 Input Devices

Input devices are used to control a VR application. VR systems typically use novel 3D input devices. The most common 3D input device is the position tracker (section 3.2.2.1), but there is a wide range of other discrete, continuous, and hybrid devices for VR systems.

3.2.1 Discrete Input Devices

A discrete input device produces individual events when the user performs some action. In desktop environments, the keyboard is a typical discrete device – each key press signals the system to do something, and no input is produced unless a key is pressed. In VR systems, keyboards may also be used, but often they are non-traditional keyboards, such as chord keyboards or soft keyboards. A chord keyboard [22] is a one-handed device with a small number of keys that allows the user to input any symbol by pressing "chords" (multiple keys held down at once). Soft or virtual keyboards do not use a specialized input device at all, but instead use virtual keys presented in the environment. The user selects these virtual keys to input symbols.

Another typical discrete input device for VR systems is the Pinch Glove™ (Figure 9). Pinch gloves are gloves with conductive cloth sewn into the fingertips, so that when two or more fingers touch one another, a signal is generated. Pinch gloves have been used for a variety of different tasks in VEs, including navigation, manipulation, menus, and symbolic input [23].

Figure 9: Pinch Gloves™, from Fakespace Labs

3.2.2 Continuous Input Devices

A continuous input device sends signals back to the host computer constantly, with or without any action by the user. The positional component of a mouse is a continuous input device used in desktop systems – it reports the X and Y position of the mouse constantly. In immersive VR systems, trackers and data gloves are the two most common continuous input devices.

3.2.2.1 Tracking Devices

As noted above, head tracking is an important component of many types of VR systems. A head tracker allows users to view the virtual world naturally using head motions, rather than indirect movements using a mouse or some other device. Many VR applications also track users' hands, bodies, or feet, or other physical objects (props). There are many different technologies used in tracking devices, including electromagnetic, inertial, acoustic, optical, mechanical, and vision-based. A complete survey of these technologies is beyond the scope of this paper. However, it is important to use tracking technologies that provide high precision, high update rates, and low levels of latency, or lag. Latency is especially crucial for head-tracked immersive VR. If the tracking system has too much latency, the virtual world will lag behind the user's head movements, possibly causing simulator sickness.

3.2.2.2 Data Gloves

Unlike pinch gloves, data gloves continuously report on the posture of the user's hand by measuring joint angles. When combined with a tracker, data gloves allow the recognition of gestures (postures + orientation or motion). This allows users to gesture naturally to interact with the VE, such as grabbing an object, waving to someone else, or giving a "thumbs-up" signal.

3.2.3 Hybrid Input Devices

Finally, we need to mention hybrid input devices – those which combine both discrete and continuous inputs. On the desktop, the mouse is a hybrid device, combining discrete buttons and continuous positional input. A large number of VR input devices are also hybrid in nature. The most common example is a tracking device that also includes discrete buttons, so that it can be used something like a 3D mouse.

4 VR Software

Current VR development software supports a wide range of VR implementations. VR software is not only concerned with 3D object generation, but also needs to allow for navigation and interaction within the 3D world. VR software also includes other features that need to be considered when selecting VR software. This include features to support importing 3D models from other systems, 3D libraries, optimization of level of detail, object scaling, rotating and translating, stereo viewing, animation, collision detection, and multi-user (avatars) networking. A good review of these features can be found in [1, 3].

There are two major categories of VR implementation software: toolkits or software development kits (SDKs), and authoring systems [3]. SDKs are programming libraries (generally written in C or C++) that provide a set of common functions with which a skilled programmer can quickly create a basic layout of the VR application. Authoring systems are mostly icon-based programs with graphical user interfaces (GUIs) to create virtual worlds without going through detailed programming. This section examines some of the available software for VR implementation.

4.1 Sense 8: World Toolkit (SDK) and WorldUp (authoring tool)

The World Toolkit (WTK) [24] is a commercial package that consists of a library of over 1000 functions written in C that enable users to rapidly develop new virtual reality applications. Using WTK, programmers build virtual worlds by writing codes to call the WTK functions.

WorldUp, a component of the WTK, is a 3D content authoring tool for real-time graphical simulations. It provides an easy-to-use graphical user interface from which users create objects and properties and design simulations. It can create or import 3D scenes, make them interactive with an easy-to-use drag and drop assembly, and can also integrate them with the industry standard tools that are already available. In adding behaviors to the objects, users can author customer behaviors or change a property of an existing behavior by writing scripts using the BasicScript language, or use property change events to trigger behaviors.

4.2 Paradigm: Multigen (authoring tool)

Paradigm [25] provides modular based commercial VR and 3D content creation. They offer an industry-leading range of fully integrated, highly automated real-time 3D database development and visual and sensor simulation tools for the IRIX™ and Microsoft Windows NT® operating systems. Some of the products available are MultiGen Creator for modeling, TerrainPro for Large Area Terrain generation, RoadPro for creating roads that meet real-world engineering standards and Vega for the creation of real-time visual and audio simulation, virtual reality, and general visualization applications.

4.3 Perilith Industrielle - Unrealty (authoring tool)

Unrealty [26] is a new innovative commercial VR creation kit. The VR kit was developed utilizing the game engine of a currently popular 3D game i.e. Unreal Tournament from Epic games. Due to ease of use and highly realistic and believable real-time images it can produce, Unrealty was used to generate a 3D walkthrough environment of the Virtual Norte Dame Cathedral of France project (Figure 10). NASA has also used Unrealty to create their Virtual International Space Station (Figure 11).

Figure 10: The VRND project

Figure 11: NASA's Virtual International Space Station project

4.4 VRML

VRML [27, 28] (an acronym for the Virtual Reality Modeling Language) allows to store descriptions of 3D worlds on the web and provide ability to transform (i.e. scale, translate, rotate, etc.) graphical objects in real time. VRML contains a number of features such as hierarchical transformations, light sources, viewpoints, geometry, animation, fog, material properties, and texture mapping (see Figure 12).

Unlike HTML, VRML also provides the technology that combines 3D, 2D, text, and multimedia into a logical model. When these media types are integrated with scripting languages and Internet utilities, an entirely new generation of interactive applications is possible.

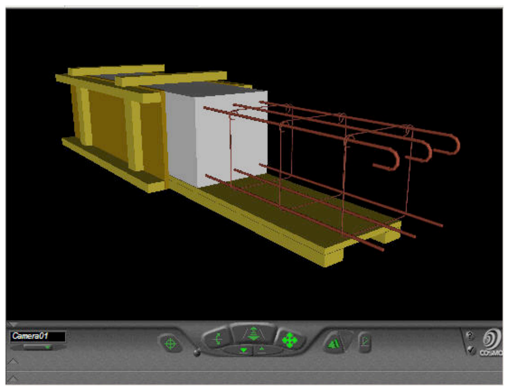

Figure-12: A VRML model of a Construction Assembly

4.5 Wild Tangent: Web Driver™

Wild Tangent has developed new 3D content creation software for the web. The whole technology evolves from Genesis 3D, which is an Open Source 3D Game Engine and it is available for public at no cost [29]. Wild Tangent's Web Driver™ has the ability to create powerful, interactive applications for the Web in super-small-sized files. The Web Driver™ 2.2 SDK when combined with the environment editor WTStudio, will provide everything that the user needs to develop interactive media applications. The best part of all, it's FREE to use.

4.6 3DState

3DState [30] specializes in 3D technology for the Internet. Their technology is suited for 3D virtual malls, 3D virtual expos and 3D web-sites. Their development tools include: WorldBuilder to create professional interactive 3D environments, TerrainBuilder to convert standard 2D topographical map into an interactive 3D world. Users can flythrough and explore this newly created terrain, or export it to WorldBuilder for further development, and 3D Webmaker Web Sites can be built in minutes using drag and drop functionality.

4.7 3D Game Engines (3DGEs)

The use of 3D Game Engines (3DGE) to create real-world VR applications is a promising new alternative to currently available commercial VR development platforms. Recent research efforts have proven that the use of 3D Game Engine, which is also known as Game Development Kits (GDKs), is a viable solution to creating visually engaging virtual environments while still maintaining a low-cost development and execution platform [31, 32]. Two of the most widely used 3D Game Engines to develop VR applications (mainly walkthroughs) are the Unreal Tournament 3DGE from Epicgames [33] and Quake 3DGE from id Software [34]. Table 1 lists examples of VR projects that utilized 3DGE for their development [35].

Recently, a group of game enthusiasts released a version of Quake for the PocketPC known as PocketQuake (see Figure 13). Using Pocket Quake, users are able to use the PocketPC to navigate through a 3D virtual environment that is fully lighted and textured. Since id Software has made it Open Source, users can create 3D models using various third party 3D level editors for Quake [32]. More information on how to create these levels is available at [36, 37, 38].

Figure 13: Pocket Quake on the Pocket PC

Year	VE Project	GDK	Developer	Description/Comments
1998	Virtual Florida Everglades National Park	**Unreal**	Project leader: Victor DeLeon	A project to educate the public and also promote ecological awareness
1998	Notre Dame Cathedral of France	**Unreal**	Digitalo Studio	Funded by UNESCO. Demo can download at http://www.vrndproject.com.
1999	Long Island Technology Center	**Unreal**	Perillith Industrielle for Rudin Management	Demo can be downloaded at http://www.unrealty.net.
1999	Heartland Business Center	**Unreal**	Perillith Industrielle	An office complex in New York.
1999	HypoVereins Bank	**Unreal**	Perillith Industrielle for Turbo D3	Virtual bank in Germany. Demo can be downloaded at http://www.unrealty.net.
2000	Virtual Graz of Austria	**Unreal**	Bongfish	Graz is the second largest city in Austria. Funded by UNESCO.
2000	Virtual International Space Station - VISS	**Unreal**	NASA Langley Research Center Spacecraft & Sensors Branch An International Virtual Space Station	Demo can be downloaded at http://www.unrealty.net.
2000	Cambridge University and Microsoft Science and Technology site in West Cambridge	**Quake 2**	Martin Centre for Architectural and Urban Studies, Cambridge University	Part of a project on using electronic communication between buildings' architects and their eventual users.
2000	CAVE Quake 3	**Quake 3**	Quake 3 Visualization and Virtual Environments Group, NCSA.	A CAVE system based on the Quake 3 Arena engine. Web-site at: http://www.visbox.com/cq3a/.
2001	CAVE UT	**Unreal Tournament**	Medical Virtual Reality Center, Department of Otolaryngology, University of Pittsburgh	A CAVE system based on the Unreal Tournament engine. Web-site at: http://www2.sis.pitt.edu/~jacobson/ut/CaveUT.html.

Table 1: Major VE projects utilizing 3D Game Engines

5 VR in the Construction – Current Research Work

What can construction project stakeholders do in a 3D virtual environment ? They can actually "climb inside" a building and visualize its elements and components from any visual perspective to evaluate the design and make modifications. They can virtually "disassemble" the components and "reassemble" them repeatedly to rehearse the construction process, develop a construction sequence, assess the constructability of the design and identify potential interference problems. They can take unlimited virtual walkthroughs of the facility and experience, in near-reality sense, what to expect when construction is complete.

This section explores some applications of VR in construction. The list of work reviewed is not intended to be exhaustive, but rather to provide an opportunity to discuss and review a range of applications associated with VR and the way it is applied in this sector.

5.1 VR in House Building

In a survey that investigated the IT systems used for product design, development modeling and sales in the British house building industry [39], over half of the questioner respondents had previously seen a demonstration of VR in the construction industry, 82% thought that it was potentially useful for their company, and 76% of the respondents indicated that it would take less than five years to see VR techniques used in their company. Specific results included:

- Use of 3D and VR can be beneficial if used early at the conceptual design process - detailed construction drawings could then be automatically generated.
- Housing developers had mixed feelings about giving users total freedom of movement around models in a VR environment - they had preservation on exposing users to views from sensitive unrealistic angles.
- VR and advanced visualization must be used with care when dealing with local authorities to avoid exposing the design/construction to other issues.

Whyte and Bourchlaghem [40] reported a study visit to Japan where three case studies were conducted to investigate Japanese house builders' use of VR. Findings indicated that the Japanese house builders have recognized the benefits of VR in construction and have been using VR technologies for over three to four years.

5.2 VR in Construction Safety and Training

Neville [41] suggested that training is important for rehearsal purposes and to prevent accidents and injuries. Barsoum *et al* [42] developed an interactive virtual training model, SAfety in construction using Virtual Reality (SAVR), to train construction workers on avoiding falls from platform-metal scaffolding. Using HMDs, users are able to interact with the VE and detect hazardous conditions (e.g. missing guardrails, loose, weak or inadequately spaced planks, inadequate connections between scaffolding components, and defective components) and attempt to eliminate it. A scoring system is used to evaluate performance of participants. SAVR comprised of two main modules; an erect module, and an inspection module. The erection module is used to demonstrate appropriate procedures to erect scaffolding. The inspection module is used to detect and correct the potential causes of falls. Sense8 WTK on an SGI platform and 3D Studio were used for creating the virtual environment and engine. An Onyx Reality Engine 2 (ORE2) from SGI was used to allow real time rendering.

Soedarmono *et. al* [43] also developed a prototype VR model for training personnel on avoiding falls during construction. Occupational Safety and Health Administration (OSHA) regulations were integrated into the model as 2D text and audio information. Warning messages (i.e. required safety standards) are displayed or announced when a user approaches a working platform in the VE from which they could fall.

5.3 VR for Project Planning and Monitoring

Although modern project management software aids the development and assessment of project schedules, their 2D symbolic representation communication among the parties involved difficult and mistake prone. Retik [44] developed an approach to tackle these issues through the use of a computer based system for visual planning and monitoring of the construction processes. The system allows the creation of a 'virtual construction project' (Figure 14) from a schedule and subsequent visual monitoring of and interaction with the progress of the simulated project.

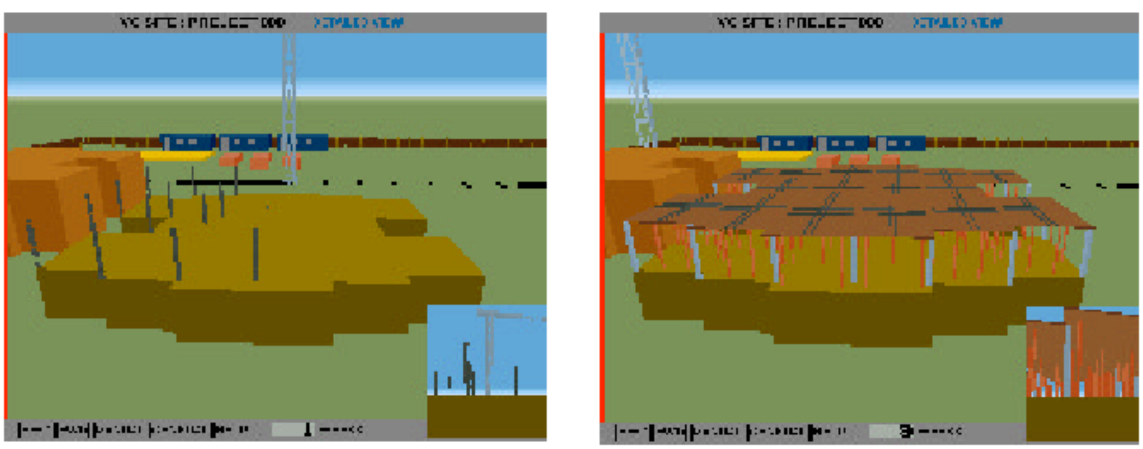

Figure 14: Images from the Virtual Construction Project system

Research in progress at the University of Teesside, UK [45], is developing the Virtual Construction Site (VIRCON), a prototype application for evaluation, visualization, and optimization of construction schedules within a virtual reality interface. The structure of the VIRCON system is designed with three main components: Project database, analysis tools and decision support components to process time critical and space critical tasks, and a visualization component to communicate the project database and analysis results through a range of interconnected graphic windows.

Mahachi *et al* [46] reported on the development of an integrated construction management tools in a virtual reality environment. This was possible through the integration of project management scheduler with cost forecasting techniques and using genetic algorithms for site-layout planning. Primavera P3^{TM} is integrated with VR to enable the simulation of construction scheduling in real-time, allowing the project planner to see the progress of construction activities on site.

Kim *et al* [47] proposed a Construction Visualization System (4D-VR, 4 Dimension-VR). The system was intended to be applied to large and complicated projects that require milestone schedule management and detailed activity control. The system has a software structure with five modules i.e. 3D CAD modeling, VR modeling, schedule data processing, linking graphic data with schedule data and visualization output modules.

5.4 Augmented VR

Webster *et al* [48] developed two experimental augmented reality systems. One prototype called "Architecture Anatomy," allows viewers to overlap graphical images of columns and rebar on top of the user's view of portions of a building architectural or structural finishes. The system was developed using C, C++, and CLIPS running on a Unix operating system. The second augmented reality prototype developed guide workers through the assembly of a space frame structure. Using bar coding technology coupled with sound files containing verbal instructions, the system guides the user to select the correct component by reading its barcode, and utilizing textual installation instructions along with sound explaining how to complete installation. The prototype was developed using Modula-3 running on an assortment of hardware under Unix, WinNT and Win95.

5.5 VR for Site layout Planning

Boussabaine *et al* [49] implemented a working VR prototype system to simulate the layout of construction site facilities. The prototype is intended to assist project managers in planning a safe and efficient site. The system allows users to create their own site layout environment, manually select and place objects representing facility and equipment, and create walk-through to view the virtual facility.

5.6 VR as an Analysis Tool

Dawood and Marasini [50, 51] developed a visualization and simulation model to address the problem which is experienced by the pre-cast concrete products industry. Problems include space congestion and long vehicle waiting times on stockyard for both the storage and retrieval of concrete products (Figure 15). The visualization model was developed using ILOG Views and the simulation model used a general-purpose simulation language, ARENA/SIMAN.

5.7 VR for Architectural Walkthrough and Preservation

Various projects and research efforts have utilized VR for architectural preservation and walkthrough purposes including: the VRND project [52] (developed by Digitalo Inc. and funded by UNESCO to electronically preserve the cathedral's historical and architectural values) and the Virtual Graz project [53] developed by Bongfish (see Figure 16). In 2000, Shiratuddin *et al* [31] utilized 3D Game Engine technology to develop a model of a mosque (Figure 17).

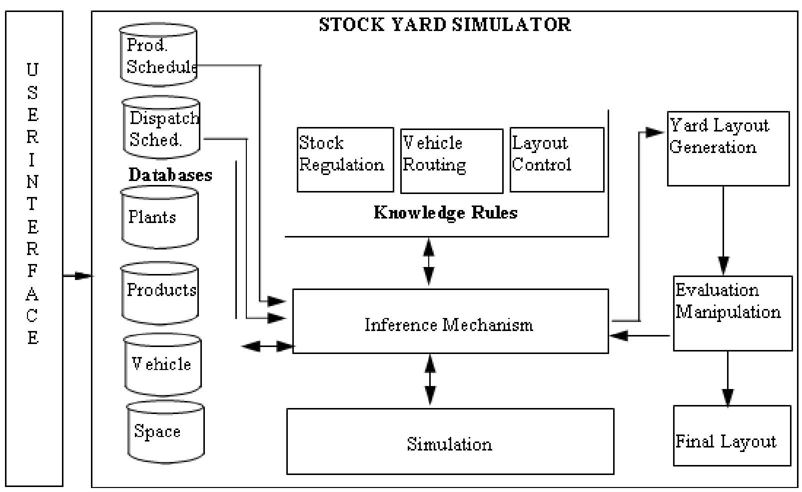

Figure 15: Stock Yard Simulator

Use of VR for visualization in the industry is demonstrated by many companies including WS Atkins, UK [54]. Various applications were developed for design review, external/internal inspection, below ground inspection, assessment of land take and space usage, sight lines, and construction sequencing. VE applications are developed from 3D models imported into native VRML.

Figure 16: Sample images from the Virtual Graz project

Figure 17: The interior of the Virtual Mosque

6 VR in Construction – Current Research Work at Virginia Tech

Through a collaborative effort between the Department of Building construction and the department of Computer Science at Virginia tech, several research efforts have been initiated to investigate the use of VR technologies in construction. This section provides an overview of some of the main VR research activities currently underway.

6.1 Evaluating the Effectiveness of VE Displays

This research project evaluates and compares the applicability, usability and effectiveness of various virtual environment (VE) displays versus other 2D and 3D representations for design review and pre-construction planning. This will allow for assessing the benefits that may be gained by adopting VE technology – benefits such as making design changes/modifications and planning decisions faster, easier, more efficiently, and more accurately. The research intends to create a mapping between display types and design/planning tasks, identifying one or more effective display modalities for each task.

Four VE displays are used in the research study; Fakespace CAVE™, HMDs (Virtual Research V8s), a tabletop display (Fakespace Immersive Workbench), a personal half-dome display (Elumens visionStation). Several industry partners, including design firms, contractors and owners, have begun to take part in this study. Each subject will view and navigate 3D models of buildings and assemblies in various stages of design and construction, using multiple displays and representations (e.g. egocentric vs. exocentric views). The subject will be asked to make decisions regarding changes to the design, the constructability of some aspect of the structure, the placement or resources, and the like, using the 3D display. Metrics will include time to reach a decision, the quality of the decision, and the subject's opinion about the suitability of the display/representation for making the decision.

6.2 The Virtual Construction Environment (VCE)

Pre-construction planning contributes significantly to the successful development and execution of construction projects. To allow for a more efficient approach to perform macro planning, a framework for a Virtual Construction Environment (VCE) for project planning has been proposed and presented [55]. The framework suggests the use of virtual reality (VR) coupled with 3D CAD and object oriented technologies to develop an interactive collaborative environment for thinking and visualizing projects in a near reality sense, prior to the actual start of construction (See Figure 18).

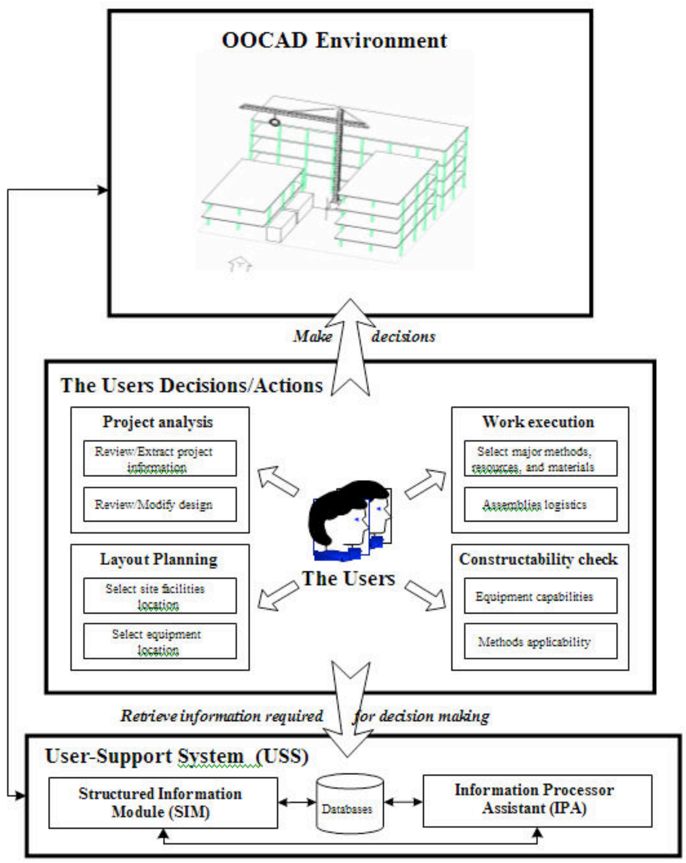

Figure 18: Proposed framework of VCE

6.3 Using VEs for Real-time Design Review and Modification

Immersive VEs can improve the design review process by allowing team members to walkthrough a realistic, life-sized model of the facility. We claim, however, that VEs can provide even more benefits to architects if team members are allowed to *interact with* and *modify* the design of the facility in *real time*, while they are *immersed* within it. This research project will implement a VE system allowing users to perform conceptual design, design review, and modification, including three interaction modules: Move, scale, and remove elements module, display/hide elements module, and massing studies module.

6.4 A Collaborative VE Utilizing 3D Game Technology

This research project [56] explores the use of game engines for implementation of a collaborative virtual environment with remote connectivity capabilities. The research utilizes the Unreal Tournament 3D Game Engine (3DGE) from Epic Games [33] to develop the framework of a collaborative environment that will allow geographically dispersed design members to virtually meet for design review (shown in Figure 19). The Unreal Tournament engine comes with a built-in multi-user support that allows for up to 16 multiple users (i.e. clients) to connect to the VE server and communicate via a basic text chat tool. The proposed work is being implemented using the Unreal Script programming language.

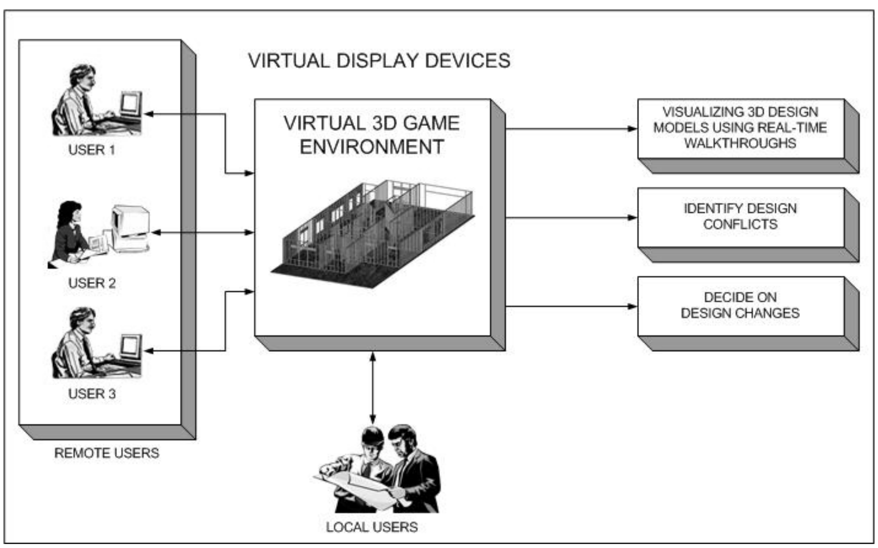

Figure 19: Remote Collaborative Virtual Environments

Research tasks include:

1. Develop additional communication mechanisms among the users connected. This task will develop advanced text messaging and voice communication modules.
2. Investigate capabilities to allow users to modify/manipulate 3D graphical elements in real time, while navigating the game engine VE.
3. Design a database structure integrated in the game engine environment to capture user design comments and store design information for design components and assemblies.

6.5 3D Visualization Using the Pocket PC

This research project [36] explores the use of the Pocket PCs for visualization of 3D models using several VR applications that support the Windows CE platform. Figure 20 depicts the proposed framework under development for investigating the current benefits and limitations of the Pocket PC and their potential use as a stand alone visualization platform.

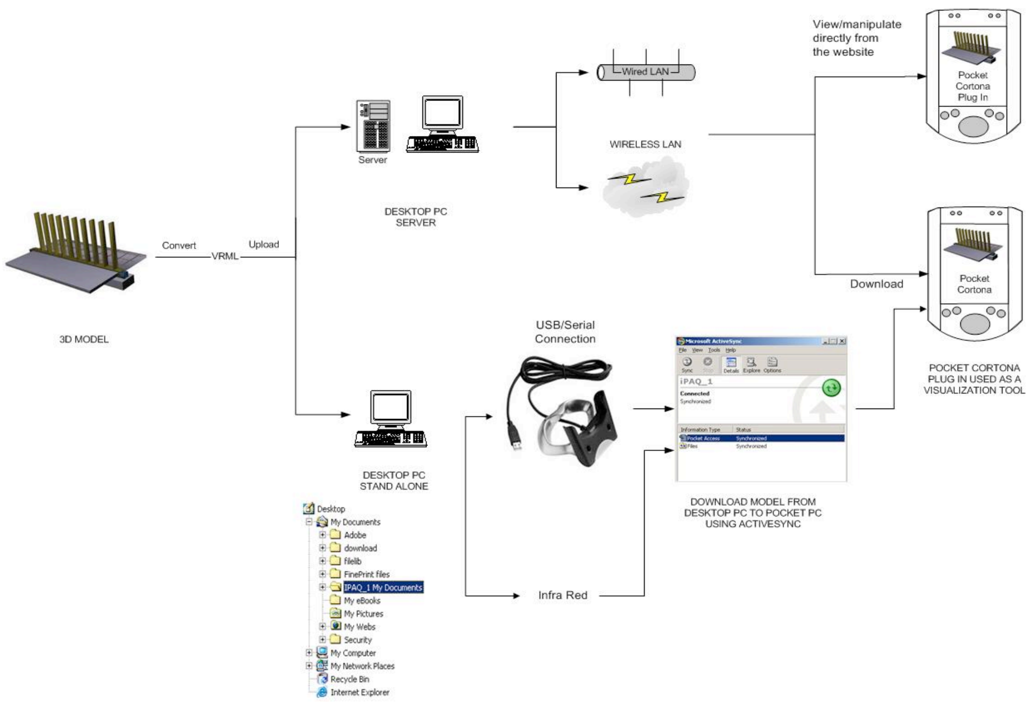

Figure 20: Framework for testing Pocket PCs with various VR applications

The development of the proposed framework currently involves the following two major tasks:

1. Identify VE applications that support the Pocket PCs and the Windows CE platform. We are currently exploring two applications; Pocket Cortona (a VRML viewer), and Pocket Quake (a compact version of the Quake game engine). Pocket Cortona, developed by Parallel Graphics [57], allows for viewing VRML files and support various navigation functions (Figure 21). Pocket Quake is a beta released 3D game environment for viewing 3D models on the Pocket PC [38].
2. Test the communication of the VE applications running on the Pocket PC with the desktop platform using a wired LAN, and wireless connection (WLAN) to investigate the different options for downloading and uploading 3D models between the two platforms, and identifying the benefits and limitations.

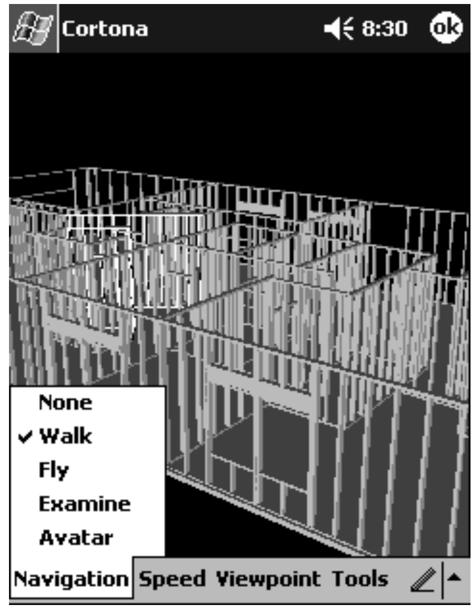

Figure 21: Interface of Pocket Cortana

6.6 An Immersive VE Training System for Disaster Relief and Assessment

Various organizations across the US are continuously creating a database of engineers that can be called on when a disaster occurs. However, many of these engineers do not have the skills necessary to assist in these situations. For example, after the World Trade Center collapse, hundreds of volunteers were needed for structural assessment of the buildings in the surrounding area. This project will develop a prototype immersive VEs to train and prepare rescue and assessment volunteers for relief and assessment efforts in collapsed buildings as a result of a large-scale disaster such as a terrorist attack, earthquake, or fire.

The short term (1-year project) of this project is to develop a detailed 3D graphical model of a collapsed facility (e.g. building) and allow users to walk through it in an immersive VE such as the CAVE. The users will be able to interact in real-time with the environment to simulate a training scenario. The level of interaction implemented will be limited. The long-term vision of this project involves the design of advanced interaction techniques. The system will also be designed to graphically predict and simulate the failure of the facility for different types of disaster scenarios.

7 Conclusion

A computer graphics problem may involve the drawing of three-dimensional (3D) objects and can be achieved either by writing a computer program using a programming language (e.g. C^{++}), or using any CAD packages (e.g. AutoCAD™). A computer animation problem introduces the dimension of time, and the goal is to make objects move in the 3D graphical environment. Implementation is achieved by writing high-level programs, but is generally helped by computer graphics libraries. An integrated animation system can make the development easier by allowing objects to be modeled and animated in one environment. A virtual reality problem is even more complex as it involves creating a 3D environment that is animated, interactive and run in real time. Virtual reality is not just concerned with moving about a virtual environment to gain a different view of a model, VR is about true interaction that can occur with all aspects of the virtual domain [2]. This might involve the touching of objects, moving objects to new positions, modifying object sizes, changing light levels, and so on.

This paper has reviewed some of the work currently being implemented to use VR in construction. There is a lot of other ongoing work that has not been discussed in this paper due to time and space limitations. However, there is much more work to be done in this field to explore its tremendous applications that can greatly benefit the construction industry as a whole.

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