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REVIEW

Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions

Muhanna A. Muhanna

King Hussein School for Computing Sciences, Princess Sumaya University for Technology, Amman, Jordan

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Taxonomy;
CAVE;
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Abstract One of the main goals of virtual reality is to provide immersive environments that take participants away from the real life into a virtual one. Many investigators have been interested in bringing new technologies, devices, and applications to facilitate this goal. Few, however, have focused on the specific human–computer interaction aspects of such environments. In this article we present our literature review of virtual reality and the Cave Automated Virtual Environment (CAVE). In particular, the article begins by providing a brief overview of the evolution of virtual reality. In addition, key elements of a virtual reality system are presented along with a proposed taxonomy that categorizes such systems from the perspective of technologies used and the mental immersion level found in these systems. Moreover, a detailed overview of the CAVE is presented in terms of its characteristics, uses, and mainly, the interaction styles inside it. Insights of the interaction challenges and research directions of investigating interaction with virtual reality systems in general and the CAVE in particular are thoroughly discussed as well.

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E-mail address: m.muhanna@psut.edu.jo

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1. Introduction

1.1. Evolution and definition of the virtual reality term

Computers are being widely used in almost all aspects of our daily activities. Currently, the concept of illiteracy can be seen evolving from not knowing how to read or write to having limited or no computer skills. One can argue that people who are fluent in computers have an advantage over those of limited computer skills in terms of employment opportunities, entertainment, literature, and socialization. Playing an important role in the current revolution of computers and technology, virtual reality is widely and increasingly used in our everyday activities as well. Nowadays, we can incorporate and benefit from virtual reality in entertainment, architecture, metrology, military, manufacturing, medicine, training, and many more areas. In his book (Cline, 2005), published in 2005, Mychilo Stephenson Cline claims that virtual reality will lead to essential changes in the lives and activities of human beings. However, enhancing virtual reality has been identified by the National Academy of Engineering to be one of the Fourteen Grand Engineering Challenges of the 21st century (National Academy, 2008).

Virtual reality has evolved over the last four decades. The concept of virtual reality or, in particular, the virtual space, has been used in several old novels and movies before being introduced in computer technology. Ivan Sutherland, however, is claimed to be the first to introduce the concept of virtual reality in his PhD dissertation (Sutherland, 1963), which was published in 1963, and his Ultimate Display (Sutherland, 1965), invented in 1965. Sutherland's dissertation, SketchPad, a Man–Machine Graphical Communication System, introduced several new ideas to the community of computer science in terms of computer graphics, virtual reality, and human–computer interaction. In 1989, however, the term of virtual reality in its modern meaning was popularized by Jaron Lanier, the founder of the Virtual Programming Languages research company (Lewis and Sound Bytes, 1994). Since then, virtual reality has been studied, developed, and used more intensively by interested researchers and scientists. Over the years, electrical engineering, mechanical engineering, computer graphics, computer engineering, physics, chemistry, biology, and other disciplines have had their impact on the evolution of the virtual reality experience that we practice today. Practitioners were focusing on the sight sense of a human being in developing, exploring, and investigating virtual reality. The focus currently is moving toward the sight, hearing, and touching senses. Some research investigations are being done on the smell and taste senses as well, such as in the Virtual Cocoon (Cocoon, 2012).

When computer scientists define the term of virtual reality, they refer to the immersive virtual reality systems and break the definition into two parts: the semantics of virtual and the semantics of reality. They then combine the two definitions into one to obtain a conceptual meaning of the term virtual reality from their own perspective. Major dictionaries define the adjective "virtual" to be nearly a particular thing that does not physically exist. The noun "reality", on the other hand, refers to a true, not imagined thing, that has a state of being real. Several scientists and researchers defined the term of virtual reality from their own perspectives, which relate to their disciplines and backgrounds. Pimentel and Teixeira, for example, defined the term of virtual reality to be: "an immersive, interactive experience generated by a computer" (Pimentel and Teixeira, 1993). A more recent definition was proposed by Brooks, who defined a virtual reality experience to be: "as any in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint" (Brooks, 1999). In Zaho (2002), the author defined virtual reality as a closed computer system that consists of a virtual environment, a physical environment, as well as a software and hardware interface, which allows interaction between a human and a computer. In their book, Sherman and Craig (Sherman and Craig, 2003), introduced another definition of virtual reality, which is described to be a medium composed of interactive computer simulations. In such a medium, the user's, or participant's, position and actions are sensed in order to replace or augment the feedback to one or more senses. This approach gives the feeling of being mentally immersed in the simulation or virtual world. A very recent, yet comprehensive, definition was introduced by the authors of Dioniso et al. (2013), who refer to virtual reality as "computer-generated simulations of three-dimensional objects or environments with seemingly real, direct, or physical user interaction".

From the evolution of these definitions, it can be seen that virtual reality is an integration of several elements, including computers, worlds and environments, interactivity, immersion, and users, who are usually referred to as participants in a virtual reality experience. Furthermore, Sherman and Craig introduced four key elements of a virtual reality experience, namely: virtual world or medium, immersion, sensory feedback, and interactivity (Sherman and Craig, 2003). Other elements have been identified too, such as the computer (Pimentel and Teixeira, 1993) and the users or participants (Brooks, 1999). Section 2 briefly describes the elements of a virtual reality experience.

1.2. Related terms and concepts

The term virtual reality was not the only one to describe such technology, system, or experience. In the 1970s, for example, Myron Krueger (Krueger, 1992) introduced the phrase artificial reality, by which he meant a technology that allows the user to physically participate in a simulation created and updated by a computer. Kruger explained that an artificial reality system tracks the participant's body, gives the virtual world some graphical representations displayed on screens, and modifies the object of the world in response to actions done by the participant. This requires analyzing the participant's movements in the context of the virtual world.

Cyberspace is another term that was coined by the science fiction novelist, William Gibson, in his 1982 and 1984 stories, "Burning Chrome" and "Neuromancer". By this term he meant "a parallel universe created and sustained by the world's computers and communication lines" (Doherty, 1994). In an interview, Gibson explained cyberspace to be a metaphor where banking transactions, stock markets, telephone calls and the Internet take place. It is a space in which geography no longer exists (Josefsson, 1994). From a computer scientist's perspective, cyberspace was defined by Sherman and Craig (Sherman and Craig, 2003) to be a space or a location residing in the participant's mind. This space is a result of technology that allows people, who are geographically away from each other, to communicate in an interactive fashion. Other newer terms that are related to virtual reality include virtual worlds, and virtual environments. A virtual world was described earlier in this section. A virtual environment, on the other hand, is considered to be both a virtual world and an instance of a virtual world presented in an interactive medium such as virtual reality (Sherman and Craig, 2003).

2. Related work

Many attempts have been done to survey the current literature of virtual reality systems. Each of these reviews discusses and outlines the status of virtual reality from a specific perspective. In Zhou and Deng (2009), for example, the authors presented the evolution of the definitions of virtual reality based on technology and immersion. They also outlined a brief history of the virtual reality technology. Furthermore, the authors discussed the key image processing techniques needed in designing virtual reality systems and virtual environments.

An older, yet comprehensive, survey of virtual reality literature was presented in Steed (1993). The paper focuses on the technologies used in virtual reality and the aspects of designing a virtual reality system, such as the interface devices, system management software and actual virtual world structure.

The author in Zhao (2011) identified ten scientific and technological problems in virtual reality from his computational point of view. The aim was to help address these problems and thus, improve the development of virtual reality applications. In fact, the author has previously published an extended version of this work in Zhao (2009), in which the author categorized virtual reality problems and identified major research and development trends in virtual reality.

A survey of augmented reality has been presented in Krevelen and Poleman (2010) in terms of technologies, applications, and limitations. The paper describes augmented reality and gives an insight of its history. It then goes into a detailed look at the key components needed to build an augmented reality system, including displays, tracking sensors, and user interfaces. The characteristics of the surveyed visual augmented reality displays are presented with a comparison of their individual advantages. Furthermore, the authors explored the different styles of user interaction with an augmented reality system along with the limitations regarding human factors of using augment reality systems. Although this paper has very interesting insights, its focus is on augmented reality rather than virtual reality. Virtual reality and augmented reality overlap in many aspects as they are both part of a bigger umbrella called mixed reality. Moreover, augmented reality can be considered part of virtual reality when combining real objects and virtual objects in a real environment.

Another related work was recently presented in (Liu et al., 2012), in which the authors reviewed the current state of melding-related techniques in virtual worlds. In particular, the authors introduced a taxonomy of consistency models that helps in providing users interacting within a shared virtual world with the illusion needed to improve their virtual experience. The taxonomy was applied to case study several shared virtual worlds. Finally, the authors discussed the challenges and promising solutions of state melding in large-scale virtual worlds.

While each of these related works, among others (Bowman, 1995; Wright and Madey, 2008), has its significant impact and contribution on exploring and outlining the status of virtual reality, little work has been done in focusing on reviewing the interaction design aspects of building virtual reality systems and the key elements needed to improve such interaction. In addition, the literature lacks a comprehensive taxonomy that can classify virtual reality systems into groups that share a common pattern of properties and the level of immersion in particular. Furthermore, and although we believe it has a great promising potential, the CAVE has not been well studied in terms of exploring the interaction challenges and research directions of building a CAVE-based application.

2.1. Objective and scope of the current paper

This paper is constructed around four main aspects: (i) virtual reality and elements of a virtual reality system, (ii) a taxonomy of virtual reality systems, (iii) the CAVE, and (iv) interaction styles used, challenges faced, and research directions in building software applications for virtual reality systems and the CAVE.

The main objective of this paper is to provide a comprehensive review of the current status of virtual reality systems and the CAVE, in particular. We believe that experts as well as new comers to the field of virtual reality, the CAVE, and human–computer interaction, would benefit from this review. For new comers, the flow of presentation works as follows: firstly, virtual reality definitions and a brief look at its evolution over the past decades are introduced. Secondly, the key elements that should be found in a virtual reality system are explored. Each one of these elements can be looked at as a measure in identifying whether a system shall be considered a virtual reality one or not. Understanding these elements is essential in order to understand the proposed taxonomy as well as the rest of the paper. Thirdly, a proposed taxonomy of virtual reality systems is presented with examples to give the reader a visual insight of current trends of virtual reality systems. Other objectives of the taxonomy are discussed at the end of this section as well. Fourthly, a deeper look at the CAVE is presented in terms of its characteristics, uses, and interaction styles. We chose to further explore the CAVE rather than other virtual reality systems because we believe that the CAVE is one of the most important systems of the evolution of virtual reality. Although the CAVE has a great potential, many of its research and development aspects, the interaction design aspect in particular, have not been well explored by researchers. Therefore, and fifthly, an exploration of the interaction design challenges of developing CAVE-based application is presented in this paper as well. The challenges identified should be carefully considered by software engineers as well as interaction designers in the early stages of the software life cycle. As a result, unpredictable software risks could be minimized. Moreover, interested researchers and practitioners could benefit from the identification of these challenges in opening the directions for future research studies and investigations that could deal with each one of the challenges and/or minimize its impact.

Many virtual reality systems have been developed over the last decades. Also, the future trend is promising in terms of the number of virtual reality systems that are being, and will be, developed. Therefore, there is a need to classify such systems into groups, where members of each group share some common patterns. In Section 3 of this paper, we present our proposed taxonomy of virtual reality systems. One of the objectives of the proposed taxonomy is to classify virtual reality systems into groups. Each group has its own properties and significance. Although different, virtual reality systems in each group share the same relationship patterns in terms of technology and level of immersion. Moreover, we believe that such taxonomy helps practitioners in focusing on a group, rather than a specific system in conducting future research studies. For example, a heuristic evaluation can be customized to one group over another according to the specific properties of the group. Another benefit of the proposed taxonomy would be in supporting the prediction of new trends in the evolution of virtual reality systems as well as identifying new systems. This, in turn, would minimize the randomization of virtual reality systems and put the technology on a clear time line.

3. Key elements of a virtual reality experience

3.1. Key element one: a virtual world (medium)

In their book (Biocca and Levy, 1995), Biocca and Levy defined the virtual world to be a space generated by a computer in which one or more users interact with one another via two-dimensional, three-dimensional, or other graphical representations called avatars. Sherman and Craig (Sherman and Craig, 2003) described it as a collection of objects in a space governed by rules and relationships. This space is not part of the real life and is manifested through a medium.

3.2. Key element two: immersion

In terms of psychology, immersion refers to being completely involved in something while in action. In other words, it is a state in which a participant becomes attracted and involved in a virtual space of an activity to an extension that his or her mind is separated from the physical space he or she is being active in.

We can experience immersion in several types of daily activities. Many novels, for example, take the readers to a new nonexistent world where they feel themselves part of it, empathize with its characters, and forget their real world and surroundings. Scientists refer to this type of immersion as mental immersion. Other examples of such an immersion include watching a movie, listening to music, and daydreaming. Physical immersion, another type of immersion, can be experienced when we become physically involved in an experience. People who achieve a physical immersion are called participants (Sherman and Craig, 2003). In a flight simulator, for example, the trainee, or participant, has to go inside a simulated cockpit to be able to interact with different objects in order to fly a virtual airplane. What is being displayed in front of the trainee, as for example shown in Fig. 1, is updated and modified according to his or her movements, instrument readings, and the environment in which the airplane is being flown.

Mental immersion, on the other hand, has different levels of immersion in a virtual reality experience. Such an experience can have a partial mental immersing or a complete one, although it is worthwhile noting that reaching a completely mental immersion in a virtual reality experience is still an active challenge for research.

Researchers have suggested other approaches for classifying immersion. For example, in their paper, Nakatsu and Tosam (Nakatsu and Tosam, 2005) introduced the terms passive immersion and active immersion. The lack or the existence of interaction is the key element that distinguishes these two types of immersion. Active immersion includes interacting with objects, whereas in passive immersion the users only receive information with no interaction. Watching a movie, for example, can be considered an instance of passive immersion. On the other hand, an artist who is concentrated on creating a scene is an example of active immersion. Therefore, a virtual reality experience should involve an active immersion. This, in turn, is achieved by implementing different interaction approaches, which are discussed further in Section 4 of this article.

Figure 1 Participants using a flight simulator (Courtesy of Wikimedia Commons).

Ermi and Mayra (Ermi and Mayra, 2005) suggested three other classifications of immersion related to games, including sensory immersion, challenge-based immersion, and imaginative immersion. Audio and visual execution of games offers a good example of sensory immersion. It can be recognized by almost everyone, even those who have less experience with games, such as parents helping their kids in a game. Challenge-based immersion can be felt when the users are able to achieve a satisfying balance of challenges and abilities. Strategic thinking and solving a logical problem are examples of such an immersion. Finally, in an imaginative immersion, participants become more absorbed with the game story and the world to the extent that they begin to have feelings for game characters. Participants in this type of immersion are given the chance to use their own imagination, empathize with characters, or just enjoy the game.

In their book, Pimentel and Teixeira (Pimentel and Teixeira, 1993) claimed that in order for a virtual world to be considered immersive, the question to be asked is whether the virtual world is real enough to suspend the participant's disbelief for a period of time. This means that an immersive experience does not require the virtual world to be as real as the physical one.

In Zhou and Deng (2009), the authors had other perspective of looking at the virtual reality from the degree of immersion, or degree of flow. If there is no immersion, then the imaginary world constructed in their minds is considered a virtual world. When people half immerse into the world, it is considered a medium virtual reality. On the other hand, "when people immerse into the world constructed in their minds, the imaginary world is considered a virtual reality".

3.3. Key element three: feedback

Feedback, or sensory feedback (Sherman and Craig, 2003), is another key element of a VR experience. Feedback gives participants the ability to observe the results (or outputs) of their activities (or inputs). A virtual display, for example, should respond to a participant moving his or her head by updating the displayed image accordingly. In other words, when the participant looks to the right, the display should show what exists on the right side of the participant in the virtual environment, and so on. This should be done in a realistic period of time and with no delays. Although the term sensory feedback is used in medicine, mechanical engineering, electrical engineering, and computer science and engineering, it points, in general, to the same action or mechanism. In medicine, for example, sensory feedback is a mechanism of communication within the sensory system. The input signal generates an output response that returns to influence the continued activity or productivity of the sensory system (Crick and Koch, 1998).

The same approach is used in VR systems. The head, hands, orientation of the torso, or other parts of the participant, are tracked in order to provide feedback in several forms, such as visual feedback, touch or haptic feedback, aural feedback, and possibly even smell and taste.

3.4. Key element four: interactivity

In a virtual reality experience, interactivity gives participants the ability to interact with and modify the virtual world. Interactivity is achieved through the use of sensors and other devices that allow participants to dynamically interact with virtual objects through navigation, direct manipulation, or other styles of interaction. In (Bowman and Hodges, 1999), Bowman and Hodges identified three interaction techniques with complex virtual environments, namely: viewpoint motion control, selection, and manipulation. The viewpoint motion control, or travel, takes place when a participant changes his or her location or orientation within the virtual environment. In other words, it is an interaction technique that gives the participant the ability to navigate and travel in the virtual world. While navigating through the environment, the participant can interact with virtual objects that reside in the environment. This interaction is done through selecting the virtual object and then manipulating its state. It is a vital element for the virtual reality system to understand, or sense, the participant's interaction and thus provide the appropriate feedback. This should be done in a real-time manner (Preddy and Nance, 2002). Otherwise, the interactivity element of the system will not hold, resulting in bad virtual reality experience.

Interacting with a virtual environment is further explored in Section 4 of this article, in which a deeper discussion of the interactivity in a virtual reality experience, the CAVE in particular, is further presented.

3.5. Key element five: participants

As with other computer systems, a user, or participant, is an essential element in any virtual reality experience. Participants vary in many dimensions and, thus, need to be studied and targeted accordingly. A new participant to a virtual reality system, for example, needs a system that minimizes the learnability aspect of its experience. An expert participant, on the other hand, needs an efficient system in terms of getting to his or her goal with the help of shortcuts and command aggregations. An infrequent participant of a virtual reality system should be provided with a system that uses less of the human memory. This leads to the importance of the user-centered design process in developing virtual reality systems. Furthermore, a relationship between a virtual reality system and its participant(s) can take the form of one-to-one or one-to-many. In a one-to-one relationship, only one participant interacts with a virtual reality system. A one-to-many relationship, on the other hand, allows many participants to interact with one virtual reality system. This level of interaction can vary from only observing what is going on a virtual world to interactively interact with the system. It is important to note here that a minimum of one participant should be interacting with a virtual reality system while other participants observe the experience. Otherwise, the interactivity element would not hold, resulting in a weak virtual reality experience.

4. A taxonomy of virtual reality systems

As discussed in Section 2 of this paper, virtual reality is becoming widely and increasingly active in terms of research, innovations, and investigations. In other words, virtual reality media, or virtual worlds, can be experienced through several forms and representations. Fig. 2 shows our proposed taxonomy of virtual reality systems. The objectives and usefulness of proposing such taxonomy were already discussed earlier. We based our classification on two factors. The first factor is the type of technology used in building the system. In particular, we studied the need of having special input and output hardware facilities in order to experience the virtual reality system. Systems that do not use such facilities are said to be 'Basic' virtual reality systems. 'Enhanced' virtual reality systems, on the other hand, require special hardware facilities as part of their systems.

The second factor that we based our classification on is the level of mental immersion. As we discussed earlier, a virtual reality system does not have to be fully immersive. Rather, virtual reality systems vary on the level of immersion introduced to the participant and are still considered to provide a virtual reality experience.

While looking at the taxonomy, Fig. 2 in particular, someone might be confused about the level of immersion of basic virtual reality systems. Thus, it is important to clarify our point of view on this issue. We believe that those systems have the least level of immersion when compared to other, enhanced, systems. In fact, the authors in (Benyon et al., 2005) consider this type of virtual reality systems to be non-immersive. We do, however, believe that mental immersion exists in those systems but with a lower level than enhanced systems. We also believe that a system that does not provide any level of mental immersion should not be considered a virtual reality system in the first place. Clarifying our view on this issue shall clarify the three levels of mental immersion used in the proposed taxonomy. The lowest level of immersion is that seen in basic virtual reality systems. A higher level of immersion can be experienced in partially immersive virtual reality systems. Lastly, the highest level of immersion is experienced in fully immersive virtual reality systems. Please note that these three levels are of ordinal order. That is, the distance between each of the levels of immersion is not clear nor specified. A

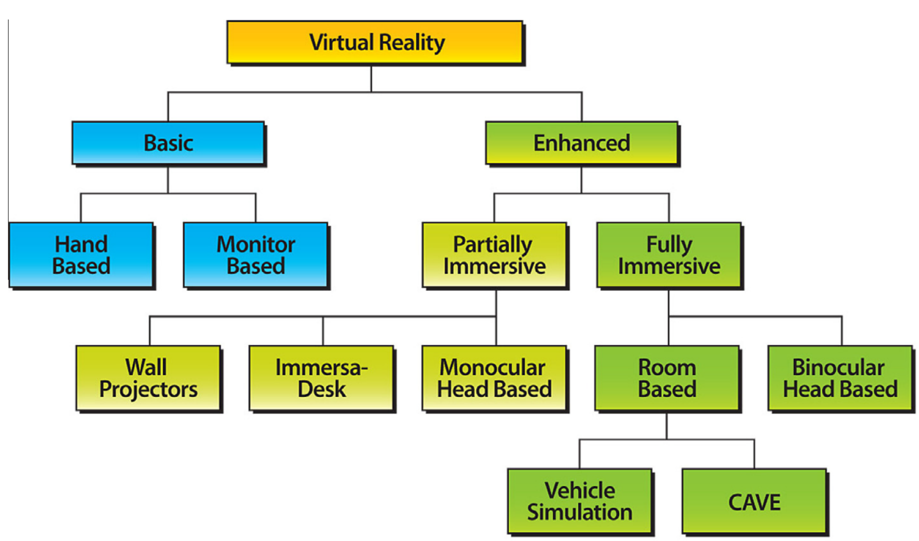

Figure 2 A proposed taxonomy of virtual reality systems.

further exploration of measuring such a distance might be considered an interesting direction of future work.

As discussed earlier, basic virtual reality systems do not need special input or output devices to display a virtual reality environment. Basic virtual reality systems are screen-based, pointer-driven, and presented by three-dimensional graphics (Heim, 2007). These systems can be divided into subcategories, such as the hand-based and the monitor-based virtual reality systems. In hand-based virtual reality systems, hand-held devices, such as cell phones, personal digital assistants, ultra mobile computers, and portable game consoles, are used to provide the virtual reality experience (Hwang et al., 2006). Fig. 2, for example, shows the Wikitude World Browser used on an iPhone. By using a digital compass and a camera on a smart phone, this hand-based system can recognize landmarks, surroundings, and points of interests in order to augment helpful data for the users, or participants, on their phones. Other, older examples of such systems can be found in Fitzmaurice et al. (1993); Wagner et al. (2005).

On the other hand, monitor-based virtual reality systems are basically desktop computers displaying three-dimensional graphics on monitors. The Fish Tank Display (Fisher et al., 1987) is an example of such a system. This display provides projected stereo images from the viewers' points of view, giving them the ability to see the third dimension on their two-dimensional desktop monitors. It is claimed that the Fish Tank Display provides only a limited virtual workspace. In other words, this type of systems has a problem of displaying virtual objects residing beyond the available workspace or on the edge of it between the viewer and the monitor (Mulder and Van Liere, 2000). Thus, it provides a low level of immersion and interactivity (Fig. 3).

Enhanced virtual reality systems use and require more powerful devices than those used in basic systems in order to create a virtual reality experience. Based on the mental immersion factor, enhanced virtual reality systems can be partially or fully immersive. Partially immersive virtual reality systems use a single projector to display a virtual world on a large screen. It can

Figure 3 Wikitude world browser used on an iPhone (Courtesy of Wikimedia Commons).

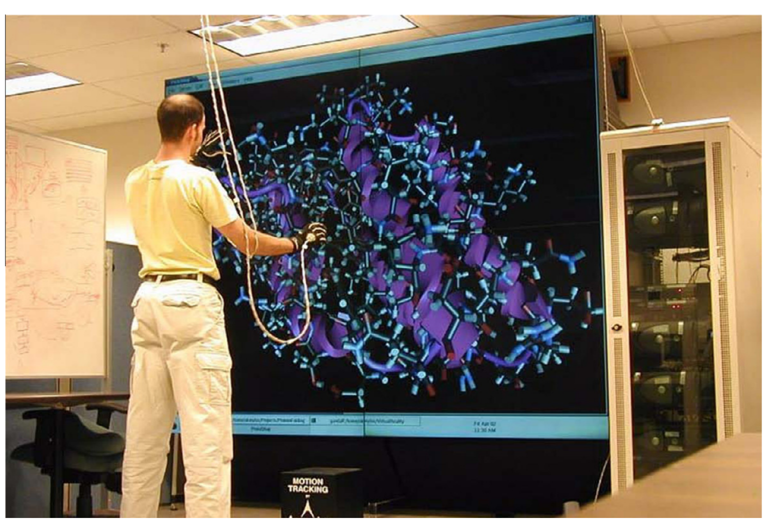

Figure 4 A participant using the IDAV's Tiled Powerwall (Keck, 2012).

be seen in enhanced wall projectors, such as the IDAV's Tiled Powerwall (Keck, 2012) shown in Fig. 4. Here, participants do not need to wear any goggles because this type of systems does not display scenes in three-dimensions. It does, however, track some parts of the body and requires the use of special gloves. Although these gloves give the participant the ability to interact with the virtual reality system, they limit his or her degrees of freedom. As seen in Fig. 4, several wired cables are usually attached to the gloves constraining the movement of the participant.

ImmersaDesk is another subcategory of partially immersive virtual reality systems. Here, the participant is required to wear special goggles to see the contents on the projection display in a three-dimensional experience. The display provides two overlapping pictures, or stereo images, of the same content so that each eye of the participant receives the same scene but from a slightly different angle (Czernuszenko et al., 1997). This gives the participant the feeling of the third dimension coming out of the display. Fig. 5 (Keck, 2012) shows a participant using an ImmersaDesk virtual reality system.

Another type of virtual reality systems is the head-based virtual reality system. It is a device worn on the head of the participant, which provides visual and aural feedback. Head-based virtual reality systems can be either partially or fully immersive. Monocular head-based systems are examples of partially immersive virtual reality, and are also considered augmented reality systems. Augmented reality is a relatively new, yet quickly expanding type of technology that combines real-world objects with virtual ones (Sherman and Craig, 2003). In other words, the user can have the ability to see virtual and real objects combined, through transparent screens, or he or she can see virtual objects with one eye and the real world with the other eye.

Fully immersive virtual reality systems provide the participant with three-dimensional virtual scenes in a large field of view. Field of view, or field of vision, refers to what a stable eye can see at a given moment (Sherman and Craig, 2003), measured in degrees. The horizontal field of view of a human, for example, can reach 180-degrees when looking forward. Field of regard, a term usually confused with field of view, refers to what an eye can see in surroundings even when the head is moved. It is measured in percentage or degrees and often used to characterize virtual reality systems.

The helmet, or head-mounted display (Melzer and Moffitt, 1997), or HMD, shown in Fig. 6, is an example of a head-based fully immersive virtual reality system, or binocular head-based. In binocular HMD, two small screens display the virtual scene to each of the participant's eyes. This feature provides a larger field of view as well as conveys the third dimension to the participant by displaying different contents on each screen. Moreover, binocular HMD systems can track the position of the head in order to provide feedback and interactivity to the participant. This, in turn, can result in a larger field of regard.

The last group in the proposed taxonomy of virtual reality systems is that of room-based systems. Here, participants achieve their virtual reality experience inside a room. Fig. 7 shows the Light Vehicle Simulator of Immersive Technologies used for training purposes. In this simulator, the participants are trained on how to respond to emergency situations and risks associated with driving light four-wheel drive vehicles on mine sites (IMM, 2012). This allows placing the trainees in scenarios that can either cost a lot to be created or cannot be built at all. Flight simulators are widely used examples of vehicle simulation systems. Fig. 8 shows the Large Amplitude Multimode Aerospace Research Simulator, or LAMARS. This simulator provides five degrees of freedom and is intended to reduce the risks of testing flights and the constraints on new aircraft designs (Linklater and Slutz, 2007).

The Cave Automated Virtual Environment, or CAVE, is another example of room-based fully immersive virtual reality systems. The CAVE is discussed in the next section in terms of main characteristics, setup, input and output devices, and human interaction styles. Through looking at the taxonomy, it is worth noting that the CAVE is a room-based, fully immersive, and enhanced virtual reality system.

Table 1 summarizes the proposed taxonomy in a tabular form. In particular, it compares the virtual reality systems presented earlier in several dimensions, namely: the need of

Figure 5 A participant using ImmersaDesk virtual reality system (Keck, 2012).

Figure 6 A participant using a binocular head-mounted display (Riecke et al., 2005).

Figure 7 A trainee using the light vehicle simulator (IMM, 2012).

special I/O devices, the constraints on the participant in order to use the system, the presence of 3D stereoscopic image to the participant, the level of immersion, the field of view, and the field of regard. In addition, the table provides some references for examples of each system.

5. CAVE automated virtual environment (CAVE)

The CAVE was invented in 1992 by a group of researchers at the University of Illinois's Electronic Visualization Lab (Cruz-Neira et al., 1992, 1993). It was designed and implemented in response to a challenge of creating a one-to-many visualization tool that utilizes large projection screens. The first developed CAVE was demonstrated at the Annual Conference on Computer Graphics, specifically within the 1992 Special Interest Group on Graphic and Interactive Techniques. As of other technology systems, the CAVE has evolved over the last two decades as well but with a slower base.

5.1. General characteristics of the CAVE

The CAVE is usually a 10′ by 10′ by 10′ cubic room that sits in a larger darkened room. The cube shape is used as an approximation of a sphere (Cruz-Neira et al., 1993). The side walls of the CAVE are made up of rear-projection screens, whereas, the floor is made of a down-, or rear-projection screen. Modern CAVE systems can project scenes to the ceiling as well, creating what is called a six-wall, or six-side, CAVE. Scenes displayed on the screens are reflected by mirrors positioned and rotated between high-resolution projectors and the screens. Projecting scenes in this particular setup guarantee a more immersive environment through casting the shadows of the

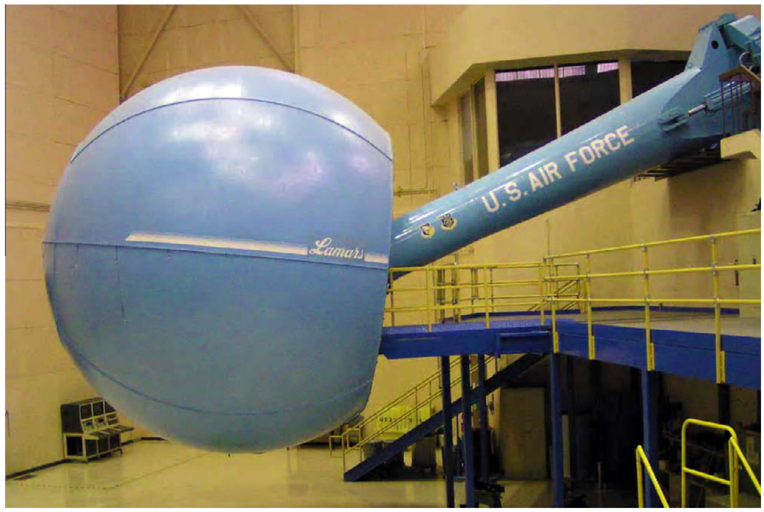

Figure 8 The LAMARS virtual reality system (Courtesy of Wikimedia Commons).

Table 1 A comparison of the different types of virtual reality systems.

Virtual reality system	Special I/O devices	Constraints	3D stereo image	Level of immersion	Field of view	Field of regard	Examples
Hand-based	None	Handheld	No	Low	Narrow	Wide	Fitzmaurice et al. (1993) Wagner et al. (2005)
Monitor-based	None	None	Yes	Low	Narrow	Narrow	Fisher et al. (1987) Mulder and Van Liere (2000)
Wall-projectors	Projector, gloves	Glove wires	No	Partial	Narrow	Narrow	Keck (2012)
Immersa-Desk	Projector, goggles	Controller wires	Yes	Partial	Narrow	Wide	Czernuszenko et al. (1997)
Monocular head-based	Helmet	Helmet weight	No	Partial	Narrow	Wide	Caballero et al. (2009)
Binocular head-based	HMD	Helmet	Yes	Full	Wide	Wide	Melzer and Moffitt (1997)
Vehicle Simulators	Special setup	None	Yes	Full	Wide	Wide	IMM (2012) Linklater and Slutz (2007)
CAVE	Special setup	Handheld wand	Yes	Full	Wide	Wide	Cruz-Neira et al. (1992)

participant behind him or her. Fig. 9 (Cabral et al., 2005) depicts an abstract design of the CAVE, its components, and equipment. Fig. 10, on the other hand, shows a real four-wall CAVE in action at the Desert Research Institute in Reno, Nevada. The participant is virtually walking inside a park of trees enjoying both a large field of view and a large field of regard. Moreover, Fig. 10 shows how a non-participated observer of the CAVE sees a blurry, or overlapped, image inside the CAVE. This overlap is mathematically calculated to convey the third dimension to the participant, who, as shown in the figure, is wearing a special pair of goggles to see a stereoscopic view of the content inside the CAVE.

Fig. 11 shows a close-up look at these goggles, which are made of liquid crystal shutter glasses synchronized via infrared emitters with projection sequence. The goggles are also used to track the head of the participant in terms of position and orientation. This is done using a 3SPACE Polhemus Isotrak sensor, whose transmitter is mounted on top of the glasses (Cruz-Neira et al., 1992). Another essential part of the CAVE is the wand, shown in Fig. 12. This is a three-dimensional controller with several buttons held by participants to allow for the interaction with the system. The three-dimensional position of the wand was the only property to be tracked (Cruz-Neira et al., 1992). Newer CAVEs, however, track the orientation of the wand as well. In other words, the wand serves as a three-dimensional mouse inside the CAVE. Furthermore, the wand has several colored buttons, each of which has its own functionality. Software developers of the CAVE have the ability to customize the functionality of each of these buttons according to the specific application being created. Using the wand, participants can point to, select, or drag and drop virtual objects as well as walk in or fly through a virtual environment.

Other input and output devices used inside the CAVE include aural systems. Some CAVEs use speakers to output aural signals to the participant. Those speakers are carefully placed inside or outside the CAVE in specific positions and

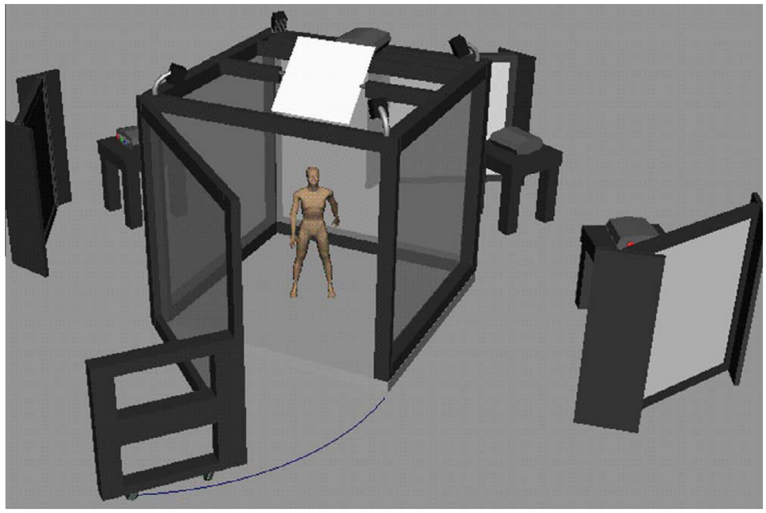

Figure 9 An abstract design of a 4-wall CAVE (Cabral et al., 2005).

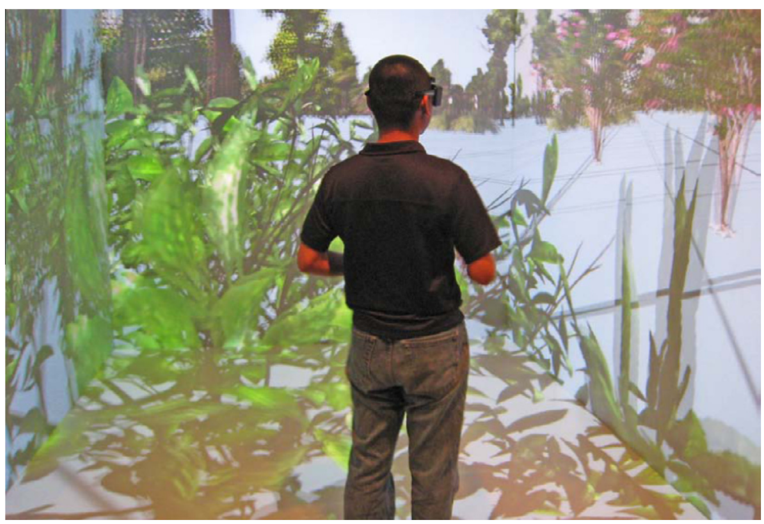

Figure 10 The 4-wall CAVE at the Desert Research Institute in Reno, Nevada.

Figure 11 Goggles and head tracker for the CAVE.

Figure 12 The wand input device for the CAVE.

accurate angles giving participants the ability not only to see three-dimensional realistic objects, but also to hear surrounding sounds around them, imitating what they would hear in the real life. Also, tactile, or haptic, systems have been used inside the CAVE as input and output devices. In Parian et al. (2009) and Hegie et al. (2010), for example, the authors introduced the Wireless Ergonomic Lightweight Device for use in the CAVE, or WiELD-CAVE. That is, a wireless input device that uses gloves to provide interaction between participants and the CAVE. Gloves can be also used to provide output by constraining the movements of the hand or sending vibration signals. When a participant, for example, grabs a virtual cup, the gloves should restrict his or her thumb from moving closer to the other fingers than the size of the cup. This yields to an immersive feeling that imitates the real world in terms of haptic, or tactile, output. Gesture interfaces that do not require the wearing of gloves are being studied by investigators as well. Based on the technology of computer vision, the authors in (Cabral et al., 2005), for example, investigated a two-dimensional gesture recognition system used for interaction in virtual reality environments, such as the CAVE. Using this system, the participant does not have to wear any gloves to interact with the CAVE.

All the above mentioned input and output devices are controlled by enhanced computers, which are connected to projectors, sensors and speakers. When a participant moves inside the CAVE, rotates his or her head, pushes a button on the wand, or maybe speaks, the computer system that controls these devices will receive the input signals and provide feedback accordingly.

5.2. Uses of the CAVE

The CAVE has been being increasingly used and explored in many projects and application domains. It can be seen used in military and training applications, education, medicine, scientific visualizations, and many other areas of human activity. For example, the CAVE has been used as an educational tool, such as in the NICE project (Johnson et al., 1998; Roussos et al., 1999). NICE is a virtual reality system that uses the CAVE to allow children to construct and interact with virtual ecosystems in a way that gives them the ability to create stories according to their interaction experience. The CAVE has also been widely used in scientific and data visualization, for example as described in (Billen et al., 2008; Ohno and Kageyama, 2007; Ohtani and Horiuchi, 2008; Symanzik et al., 1996). In addition, the use of CAVE has been tried for medical applications, e.g., in (Zhang et al., 2003) and (Zhang et al., 2001) a virtual environment was introduced for tensor magnetic resonance imaging. This gave scientists and doctors the ability to study the white-matter structures and perform advanced planning for brain tumor surgeries. The CAVE has been used in entertainment as well. The CaveUT system (Jacobson and Hwang, 2002; Jacobson, 2003), for example, is a VR entertainment environment system that supports the ability to render the Unreal Tournament game engine inside the CAVE. Learning through entertainment using the CAVE was also explored, for example in (Roussou, 2004), where the author investigated interactivity in virtual environments, including the CAVE, through a learning-by-play system for children. Second Life, a popular game for desktop computers, has been also explored in CAVE. For instance, Second Life has been used as a case study in the development of interaction methods inside the CAVE (Kuka et al., 2007). Areas of applications for CAVE are expanding constantly as this complex type of VR system offers many powerful technical capabilities.

5.3. Interaction inside the CAVE

Researchers have been studying different approaches and styles to bring an efficient and effective interaction between the human participant and the CAVE. In Sherman and Craig (2003) it is claimed that the more experience practitioners will gain in the new virtual reality medium and the more new effective techniques they develop, the more powerful and useful virtual reality systems will become. So far, direct manipulation and navigation are considered the core styles of interaction inside the CAVE. In addition, Bowman and Hodges (Bowman and Hodges, 1999) considered 'selection' to be a third interaction technique with complex virtual environments.

We do believe, however, that selection is an essential part of direct manipulation, and thus, would not consider it an interaction style of its own. This is further discussed in the next subsections. Investigations are being conducted to enhance these styles as well as explore other styles of interaction with virtual reality systems and the CAVE in particular. Such styles may include menus, command line language, natural language, and voice communication.

5.4. Direct manipulation

Direct manipulation was introduced by Ben Schneiderman in 1983 (Schneiderman, 1983) as an interaction style that allows the user to physically interact with the operating system through the use of graphical representations. It is part of the Object-Action interface model, in which the user starts his or her interaction by selecting an object and then selecting the action to be performed on that object. The main characteristics of direct manipulation include a continuous visual representation of objects and actions, immediate feedback, and revisable actions (Schneiderman et al., 2009). The nature of virtual reality systems, the CAVE in particular, requires to have a continuous visual representation of virtual objects and related actions. Moreover, immediate feedback, as discussed earlier, is a key element of virtual reality systems. Revisable actions, however, should be carefully considered when applied to the CAVE. In other words, giving a CAVE's participant the ability to undo a specific action, which he or she already did, may minimize the mental immersion element of the virtual reality experience. This can be an advantage for some applications or specific tasks and a disadvantage for others.

Virtual reality systems, in general, have four styles of interaction in terms of direct manipulation, including direct user control, physical control, virtual control (Mine, 1995), and agent control (Sherman and Craig, 2003). These controls are extensively used in CAVE-based applications. In direct user control, participants use their gestures or gazes to directly interact with the system. This imitates how people interact with objects in the real life. Examples of direct user control include looking at a virtual tree, grabbing a virtual box, etc. Physical control, on the other hand, allows a participant to interact with the virtual environment using a physical device, such as a wand, shown in Fig. 12, a steering wheel, or a glove. Pushing a specific button on the wand, for example, can be used to pick a virtual object. Physical control and virtual control have the same principles except the fact that the latter places the control devices inside the virtual environment. An example of such control could be a participant turning on the lights in a virtual room by toggling a virtual light switch. Agent control is another style of manipulation in CAVE. It gives the participant the ability to communicate directly with an intelligent agent, who is a person or a computer-controlled entity, in order to perform a specific action. Communication with the intelligent agent can take the form of voice, the form of gestures, or other forms.

5.5. Navigation

Navigation interfaces are being widely used in computers (Burigat et al., 2008). In particular, navigation can be seen in Internet browsers (Vittorio, 1998), hierarchal menus (Wang and Shen, 2005), map explorations (Chittaro et al., 2008), and desktop interfaces (Haik et al., 2002). In CAVE, navigation, or locomotion, is achieved through way-finding and travel (Sherman and Craig, 2003). In other words, to navigate through a virtual environment, a participant needs to know his or her current position and move toward a destination. The way-finding process can be divided into cognitive mapping and way-finding plan development (Chen and Stanney, 1999). Cognitive mapping is a mental process that includes acquiring, coding, storing, recalling, and decoding information about the relative locations and attributes of an environment (Kitchin, 1994). Aids of way-finding have been explored and investigated by interested researchers. For example, in (Vila et al., 2003) it has been found that the intention to take either a left turn or a right turn while navigating a virtual world is influenced by gender. Multiscale navigation of 3D scenes was also introduced in (McCrae et al., 2009). Travel, on the other hand, is the process of moving from the current position to the destination. This can take the form of flying, walking, riding, skiing, or jumping. Fig. 13 summarizes the processes and subprocesses of navigation in CAVE.

5.6. Other styles of interaction in CAVE

Participants could interact with a CAVE through other styles of interaction. In menu selection, for example, a set of items could be listed in one of the CAVE screens for the participant to choose from. When, how, and where should the participant effectively interact with a CAVE using menu selection are philosophical questions that need to be further investigated. Natural language and voice communication can be also used in CAVE. Here, the participant can speak while the CAVE listens, recognizes, processes, and sends feedbacks to the participant.

Another style of interacting with a CAVE involves someone residing outside the CAVE. In other words, someone, who is not in CAVE, can interact with the underlying simulation and structure of the world being displayed in CAVE. In (Sherman and Craig, 2003), the authors refer to this type of interacting with a virtual reality system as metacommands. Examples of metacommands may include loading new scientific data, modifying the configuration of a currently running scenario, monitoring the behavior of participants, etc. Using metacommands to interact with a CAVE, a user can use a desktop computer, a laptop, a handheld device, his or her gestures, or other devices to interact with a CAVE from outside.

6. CAVE interaction design: challenges and research directions

Many challenges can be encountered when developing applications for CAVE-based virtual reality applications, which need to be more investigated and studied by interested researchers. Table 2 summarizes these challenges, which are further discussed in the rest of this section.

From the requirements engineering perspective, more research studies are recommended in terms of the available data-gathering techniques as well as advantages and disadvantages of using a specific technique over another for a large CAVE-based project. Another related area that needs more exploration is investigating conceptual models for the CAVE. Several conceptual models and interface metaphors

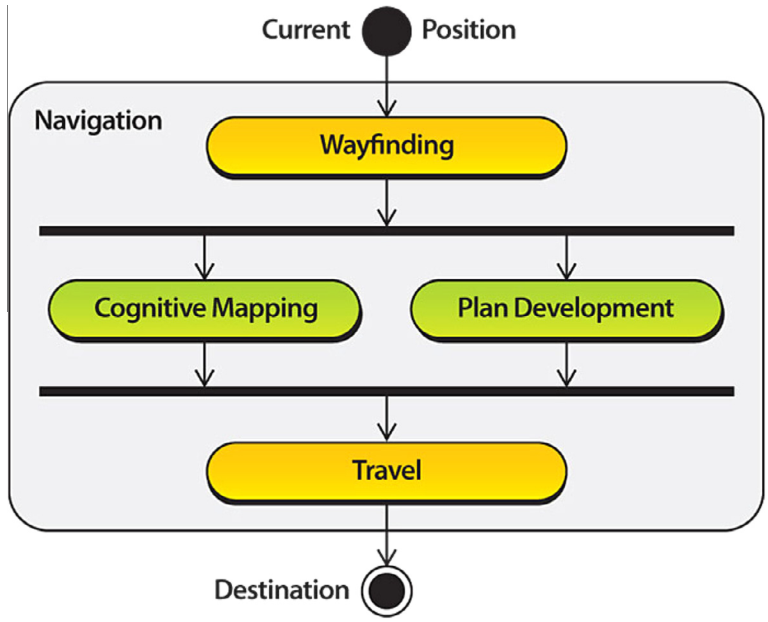

Figure 13 Processes and sub-processes of navigation.

Table 2 A summary of the explored challenges and research directions.

Field	Category	Challenges and research directions
Task analysis	Requirements engineering	– Which data-gathering technique to use
	Software design	– Which software architecture to use? – Which model diagram(s) provide a better insight for a CAVE-based application?
Development and coding	Prototyping	– How to create 3D low-fidelity prototypes? – Which prototype technique to use?
	Programming	– A survey of available programming languages for building CAVE-based applications. – A survey of the commercial-off-the-shelf-tools (COTS) that could facilitate the design with reuse
Hardware devices	Input/output	– Understand the underlying structure of each device – What are good practices to minimize the lag between input and output devices used in the CAVE? – How to minimize the use of I/O devices that constraint the participant?
Use	User experience	– How can we imitating the participant's energy and fatigue? – Walking in place vs. real walk. – Can we use prop devices to convey real devices? – How to maximize the degrees of freedom for participants interacting with the CAVE
	Learnability	– What is the best conceptual model for the CAVE? – Does the desktop metaphor fit the CAVE needs? – How to minimize the need of an expert to run and operate a scenario inside the CAVE?
Evaluation	Simulations and emulators	– A need to survey what is currently available

can be adapted from the desktop metaphor and transferred to the CAVE. Such a transfer has to be carefully explored and studied, though, to see if it fits effectively and efficiently for the CAVE or not. Coming up with new conceptual models and interface metaphors that are targeted specifically for the CAVE could have a great influence in the development of CAVE-based applications as well.

In addition, research on software engineering aspects of CAVE-based simulations needs to be further performed. Diagrams, software models, architecture structures, methods, and paradigms used in data interpretation and task analysis would be useful objects of study in the software engineering domain. Designers and developers for the CAVE will need to adapt to a specific data interpretation and analysis methods by knowing the advantages and disadvantages of each possible method and activity for the development of applications for the CAVE rather than for a desktop computer.

Sketching, storyboarding, index cards, and wizard of Oz (Green and Wei-Haas, 1985) are examples of low-fidelity prototyping (Sharp et al., 2007). All these, and their possible combinations, could be researched as well to evaluate their applicability to CAVE. However, it is likely not a straightforward approach to go with one method without conducting a deep study of its benefits as compared with other prototyping methods. In fact, the CAVE introduces three-dimensional presentations, which undoubtedly are more challenging to sketching, consume more time, and require more creativity and imagination than the regular two-dimensional presentations.

Although the financial requirements to build and install a CAVE are much higher than that of a desktop computer, simulators and emulators can be enhanced to imitate the real CAVE in desktop applications. Being able to use three-dimensional goggles, the wand, and other input and output devices while being connected to a desktop computer running a simulation of the CAVE may have a good impact on the development process. Imitating the hardware specifications of the real CAVE in a simulator or an emulator would also increase the accuracy of developing and evaluating applications for the CAVE without the need to do evaluations inside it. This would have another great impact at least for the early versions of new designs. Other evaluation methods for the CAVE may be also studied by interested researchers in terms of usability and case studies.

As discussed in the previous sections, several input and output devices are used in a CAVE system. Therefore, designers and developers of CAVE-based applications should carefully study the underlying structures of these devices. In Preddy and Nance (2002), for example, the authors discussed how the refresh rate of the graphical component inside the CAVE is usually faster than that of a motion device. Moreover, they brought the question of whether a shared memory in a CAVE-based simulation should be used synchronously or asynchronously. Another paper (Macedonia and Zyda, 1997), however, recommended the use of asynchronous data sharing if the simulation is in real-time. In order for a CAVE-based application to maintain the element of mental immersion, the lag between tracking the participant's actions and rendering the updated images to the screen, sounds to the speakers, signals to haptic devices, or smells and flavors should be minimized.

Furthermore, using critical applications in CAVE introduces more complex challenges. Using CAVE in training for a real, "live" scenario, for example, is not a reliable approach yet. In other words, many aspects of the current technology have to be further developed to make the CAVE experience as real as possible. Constraining the movements of the participant is one example of such aspects. Research has been conducted to imitate walking in a virtual environment by pushing a button, walking-in-place, real walking (Usoh et al., 1999), or walking in a rotating sphere (DIPS, 2012). Although this was not well explored in CAVE, it will still bring up the challenge of imitating the participant's energy and fatigue. A participant running in a virtual training inside the CAVE, for example, will not lose the same amount of energy when he or she runs in the same scenario in real life. Constraints could be also explored in other haptic devices in terms of touching, grabbing, kicking, etc. Moreover, future input and output devices for the CAVE could provide the ability to smell and taste.

In fact, several scientists have introduced what they call the real virtuality, or the virtual cocoon (Cocoon, 2012). That is, a head-based virtual reality technology that lets you see, hear, smell, taste, and touch. Although this technology is in its first stages, smell and taste in particular, it could enhance the user's interaction experience inside the CAVE in many directions. Three-dimensional computer graphics is another aspect that has a great impact on bringing the CAVE to a higher level of reality for simulating critical scenarios. Also, the use of prop devices in CAVE could certainly have its own positive impact. For example, in training a soldier to operate a gun, a wand will not convey the same experience as an actual gun. This, in turn, will bring up the challenge of having several input and output devices for each scenario. Vehicle simulators solve this issue by providing the actual used devices inside the simulation but at a very high cost. An alternative approach to this challenge might be something similar to the Nintendo Wii Remote, which supports many prop accessories on top of one device. Fig. 14 shows how the same Wii Remote is used to convey several props for different purposes.

Figure 14 Prop accessories for the Nintendo Wii remote (Courtesy of Wikimedia Commons).

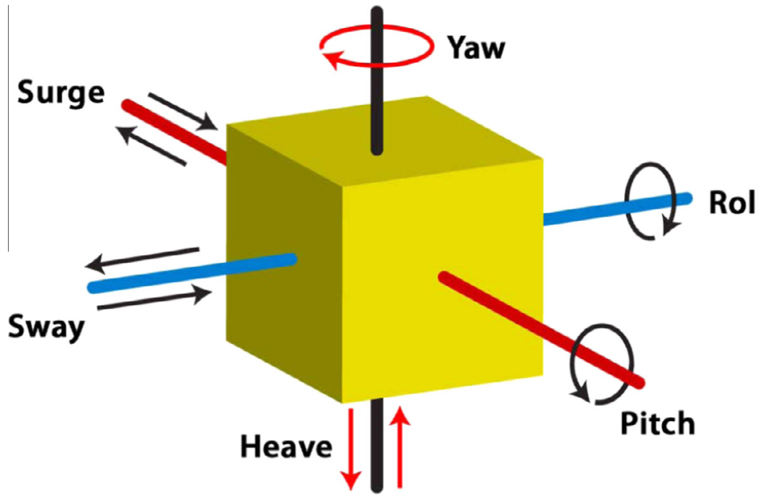

Figure 15 A cube with six degrees of freedom.

Other research and development directions can be considered in this domain as well. The study of getting more than one CAVE to collaborate with each other, for example, may have a great benefit to the development of CAVE-based applications. Effective collaborative learning currently interests many researchers and practitioners (Zheng et al., 2014). In their paper Preddy and Nance (2002), the authors discussed the need to have a standardized application-programming interface, or API, that provides the ability of working with multiple levels of abstraction to support the portability of virtual environment interfaces. Furthermore, the collaboration of two or more CAVEs, a desktop computer and a CAVE, a remote computer and a CAVE, or a mobile device and a CAVE can have many beneficial uses. In a military training session, for example, the instructor can use a desktop computer to create a scenario for the trainees who are inside several CAVEs working as a team to go through that scenario. Another use would include a competition of teams, who collaborate in several CAVEs for a specific purpose. This may also raise the need to investigate the possibility of allowing two or more participants to interact inside one CAVE.

Programming libraries and platforms for building CAVE-based applications is another area that needs to be further explored. Currently, the main libraries and APIs used for building CAVE applications include CAVELib (CAVELib, 2012), FreeVR (FreeVR, 2012), VR Juggler (Juggler, Juggler, 2012), Hydra (Hoang, 2012), and several others. Also, a CAVE application developer needs to know OpenSG or OpenGL to create interactive three-dimensional graphics. Other tools and libraries might be also needed to output voice, smell, taste, and touch. Therefore, running and operating a simulation or a training scenario inside the CAVE will bring up the challenge of having an expert programmer available. In other words, the learning curve of creating, running, or modifying a scenario in CAVE is long and needs to be minimized.

It can be clearly seen that physical immersion is an essential element of a CAVE experience. Therefore, it is important to give participants the control and freedom needed to get them to physically immerse in a virtual environment. Many research investigations have been, and still are, done to give participants the most possible freedom of interacting with a virtual reality system without being constrained to a specific device. Degrees of freedom, or DOF, a term often used in mechanics, is the number of independent position movements a body can have in a particular space (Pennestri et al., 2005). Fig. 15 shows a cube in a three-dimensional space. The cube has six degrees of freedom, including rotating around the z-axis, or yawing, rotating around the y-axis, or pitching, rotating around the x-axis, or rolling, moving up and down, or heaving, moving left and right, or surging, and moving forward and backward, or swaying.

Giving participants the highest possible degrees of freedom in a CAVE has a great impact on the interactivity element. If the head rotation is constrained, for example, the participant would not be completely satisfied, nor immersed, in his or her virtual reality experience. Moreover, interactivity ensures that multiple execution scenarios are possible in the same system.

7. Conclusions

In this article, we presented a comprehensive literature review of virtual reality systems in general and the CAVE in particular. In particular, we presented the key elements that should be available in a computer system in order to consider it a virtual reality one. Furthermore, we introduced our proposed taxonomy of the virtual reality systems. We based our taxonomy on the technologies used to build the virtual reality systems and how immersive those systems are. We believe that the main contribution of this taxonomy is to help interested practitioners in focusing on a class of virtual reality systems, rather than a specific system in conducting future research studies. The taxonomy would also support the prediction of new trends in the evolution of virtual reality systems and identify new systems. Out of the many classifications of systems outlined in the proposed taxonomy, we specifically focused on the CAVE. Our main rationale here is based on our experience with the CAVE as we believe that it is one of the most important systems of the evolution of virtual reality. However, many of the CAVE's research and development aspects, the interaction design aspect in particular, have not been well explored by researchers. Therefore, we explored the different interaction styles used to interact with a scenario running in a CAVE as well as identified the interaction design challenges of developing CAVE-based application. In addition, we aimed at discussing our review findings of the current status of research investigations in the area of human–computer interaction, virtual reality, and the CAVE, and what we believe needs to be further explored and studied.

References

Benyon, D., Turner, P., Turner, S., 2005. Designing Interactive Systems. Addison-Wesley.

Billen, M.I., Kreylos, O., Hamann, B., Jadamec, M.A., Kellogg, L.H., Staadt, O., Sumner, D.Y., 2008. A geoscience perspective on immersive 3D gridded data visualization. Comput. Geosci. 34 (9), 1056–1072.

Biocca, F., Levy, M.R., 1995. Communication in the Age of Virtual Reality, first ed. Lawrence Erlbaum.

Bowman, D.K., 1995. International survey, virtual environment research, computer,. IEEE Comput. Soc. 28 (6), 57–65.

Bowman, D., Hodges, L., 1999. Formalizing the design, evaluation and application of interaction techniques for immersive virtual environments. J. Visual Lang. Comput., 37–53.

Brooks, F.P., 1999. What's real about virtual reality? IEEE Comput. Graphics Appl. 19 (6), 16–27.

Burigat, S., Chittaro, L., Parlato, E., 2008. Map, diagram, and webpage navigation on mobile devices: the effectiveness of zoomable user interfaces with overviews, Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI'08), Amsterdam, Netherlands, September 2008, pp. 147–156.

Caballero, F., Maza, I., Molina, R., Esteban, D., Ollero, A., 2009. A robust head tracking system based on monocular vision and planar templates. Sensors 9 (1), 24–43.

Cabral, M. C., Morimoto, C. H., Zuffo, M. K., 2005. On the usability of gesture interfaces in virtual reality environments, Proceedings of the 2005 ACM Latin American Conference on Human–Computer Interaction (CLIHC'05), ACM Press, Cuernavaca, Mexico, October 2005, pp. 100–108.

CAVELib, 2012. Mechdyne Corporation, Accessed September 8, at www.mechdyne.com.

Chen, J.L., Stanney, K.M., 1999. A theoretical model of wayfinding in virtual environments: proposed strategies for navigational aiding. Presence: Teleoperators Virtual Environ. 8 (6), 671–685.

Chittaro, L., Burigar, S., Gabrielli, S., 2008. Navigation techniques for small-screen devices: an evaluation on maps and web pages. Int. J. Human–Comput. Stud. 66 (2), 78–97.

Cline, M.S., 2005. Power, Madness & Immortality, The Future of Virtual Reality. University Village Press.

Cocoon, 2012. Virtual reality technology that lets you see, hear, smell, taste and touch, Engineering and Physical Sciences Research Council, Pioneering Research and Skills. Accessed October 2, 2012 at http://www.epsrc.ac.uk/newsevents/news/2009/Pages/virtualreality.aspx.

Crick, F., Koch, C., 1998. Consciousness and neuroscience. Cerebral Cortex 8 (1), 97–107.

Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., Kenyon, R.V., Hart, J.C., 1992. The CAVE: audio visual experience automatic virtual environment. Commun. ACM 35 (6), 64–72.

Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., 1993. Surround-screen projection-based virtual reality: the design and implementation of the CAVE, Proceedings of the 20th ACM Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH'93), Anaheim, CA, USA, August 1993, pp. 135–142.

Czernuszenko, M., Pape, D., Sandin, D., DeFanti, T., Dawe, G.L., Brown, M.D., 1997. The ImmersaDesk and infinity wall projection-based virtual reality displays. ACM SIGGRAPH Comput. Graphics 31 (2), 46–59.

Dioniso, J.D., Burns III, W.G., Gilbert, R., 2013. 3D virtual worlds and the metaverse: current status and future possibilities. ACM Comput. Surv. 45 (3).

DIPS, 2012. Discoveries and breakthroughs inside science, the new virtual reality, Human-Interface Engineers Create Virtual Reality Experience by Letting Users Walk in Rotating Sphere, Accessed May 14, at www.aip.org/dbis/stories/2006/15153.html.

Doherty, M. E., Jr., 1994. Marshall McLuhan Meets William Gibson in "Cyberspace", CMC Magazine, September 1994, pp. 4–5.

Ermi L., Mayra, F., 2005. Fundamental components of the gameplay experience: analyzing immersion, Proceedings of the Second Digital Games Research Association's International Conference (DiGRA'05), pp. 15–27.

Fisher, S. S., McGreevy, M., Humphries, J., Robinett, W., 1987. Virtual environment display system, Proceedings of the 1986 Workshop on Interactive 3D Graphics, Chapel Hill, pp. 77–87.

Fitzmaurice, G.W., Zhai, S., Chignell, M., 1993. Virtual reality for palmtop computers. ACM Trans. Inf. Syst. 11, 197–218.

FreeVR, 2012. Virtual Reality Integration Library, Accessed August 22, at www.freevr.org.

Green, P., Wei-Haas, L., 1985. The Wizard of Oz: a Tool for Rapid Development of User Interfaces, Technical Report, number UMTRI-85-25.

Haik, E., Barker, T., Sapsford, J., Trainis, S., 2002. Investigation into effective navigation in desktop virtual interfaces, Proceedings of the Seventh ACM International Conference on 3D Web Technology, Tempe, Arizona, pp. 59–66.

Hegie, J.M., Kimmel, A.S., Parian, K.H., Dascalu, S., Harris, F.C., 2010. WiELD-CAVE: wireless ergonomic lightweight device for use in the cave. J. Comput. Methods Sci. Eng. 10 (1,2), 177–186, Suppl. 2.

Heim, S., 2007. The Resonant Interface: HCI Foundations for Interaction Design. Addison-Wesley.

Hoang, R., 2012. Hydra, High Performance Computation and Visualization Lab, University of Nevada, Reno, Accessed July 10, at http://www.cse.unr.edu/hpcvis/hydra.

Hwang, J., Jung, J., Yim, S., Cheon, J., Lee, S., Choi, S., Kim, G.J., 2006. Requirements, implementation and applications of hand-held virtual reality. Int. J. Virtual Reality 5 (2), 59–66.

Immersive Technologies, 2012. Light Vehicle Simulator Launched to Improve Site Safety, 2008, Accessed July 23, at http://www.immersivetechnologies.com/news/news2008.

Jacobson, J., Hwang, Z., 2002. Unreal tournament for immersive interactive theater. Commun. ACM 45 (1), 39–42.

Johnson, A., Roussos, M., Leigh, J., Vasilakis, C., Barnes, C., Moher, T., 1998. The NICE project: learning together in a virtual world, Proceedings of the Virtual Reality Annual International Symposium, Atlanta, GA, USA, March 1998, pp. 176–183.

Josefsson, D., 1994. I don't even have a modem: an interview with William Gibson, Dan Josefsson Artiklar and Blogg, November 1994, Accessed August 21, 2012 at http://josefsson.net/gibson/.

Juggler, V. R., 2012. The VR Juggler Suite, Accessed June 12, at http://vrjuggler.org/.

Keck, W. M., 2012. Center for Active Visualization in the Earth Sciences, KeckCAVES, Accessed July 18, at www.idav.ucdavis.edu/~okreylos/ResDev/KeckCAVES.

Kitchin, R.M., 1994. Cognitive maps: what are they and why study them? J. Environ. Psychol. 14, 1–19.

Krevelen, D., Poleman, R., 2010. A survey of augmented reality technologies, applications, and limitations. Int. J. Virtual Reality 9 (2), 1–20.

Krueger, M. W., 1992. An Architecture for artificial realities, Proceedings of the 37th IEEE Computer Society International

Conference (COMPCON'92), San Francisco, February 1992, pp. 462–465.
Kuka, D., Lindinger, C., Hortner, H., Berger, F., Zachhuber, D., 2007. Applying second life to a CAVE-like system for the elaboration of interaction methods with programmable interfaces, Proceedings of the ACM SIGGRAPH 2007 Posters, San Diego, California, USA, 2007, pp. 157.
Lewis, P. H., 1994. Sound Bytes, He Added Virtual to Reality, The New York Times, September 25, p. 37.
Linklater, A. Slutz, J., 2007. Exploring the large amplitude multi-mode aerospace research simulator's motion drive algorithms, Proceedings of the AIAA Modeling and Simulation Technologies Conference, South Carolina, 2007, pp. 253–264.
Liu, H., Bowman, M., Chang, F., 2012. Survey of state melding in virtual worlds. ACM Comput. Surveys 44 (4), 21–46. Article 21.
Macedonia, M.R., Zyda, M.J., 1997. A taxonomy for networked virtual environments. IEEE Multimedia 4 (1), 48–56.
McCrae, J., Mordatch, I., Glueck, M., Khan, A., 2009. Multiscale 3D navigation, Proceedings of the 2009 ACM Symposium on Interactive 3D Graphics and Games, Boston, Massachusetts, February 2009, pp. 7–14.
Melzer, J.E., Moffitt, K., 1997. Head Mounted Displays: Designing for the User. McGraw Hill.
Mine, M., 1995. Virtual Environment Interaction Techniques, UNC Chapel Hill Computer Science Technical Report, TR95-018.
Mulder, J.D. Van Liere, R., 2000. Enhancing fish tank virtual reality, Proceedings of the IEEE Conference on Virtual Reality, New Jersey, pp. 91–98.
Nakatsu, R. Tosam N., 2005. Active immersion: the goal of communications with interactive agents, Proceedings of the Fourth International Conference on Knowledge-Based Intelligent Engineering Systems and Allied Technologies, Brighton, pp. 85–89.
National Academy of Engineering, 2008. Grand Challenges for Engineering. National Academy of Engineering, Washington, DC, USA.
Ohno, N., Kageyama, A., 2007. Scientific visualization of geophysical simulation data by the CAVE VR system with volume rendering. Phys. Earth Planet. Inter. 163 (4), 305–311.
Ohtani, H., Horiuchi, R., 2008. Scientific visualization of magnetic reconnection simulation data by the CAVE virtual reality system. Plasma Fusion Res. 3 (1), 45–54.
Parian, K., Hegie, J., Kimmel, A., Dascalu S. M., Harris, F. C., Jr., 2009. WiELD-CAVE: wireless ergonomic lightweight device for use in the CAVE, Proceedings of the ISCA 18th International Conference on Software Engineering and Data Engineering (SEDE '09), Las Vegas, NV, pp. 79–84.
Pennestri, E., Cavacece, M., VitaON, L., 2005. The computation of degrees-of-freedom: a didactic perspective, Proceedings of the 2005 ASME International Design Engineering Technical Conferences, ASME ETC'05, Long Beach, California, September 2005, pp. 1–9.
Pimentel, K., Teixeira, K., 1993. Virtual Reality: Through the New Looking Glass. Intel Windcrest.
Preddy, S. M. Nance, R. E., 2002. Key requirements for CAVE simulations, Proceedings of the 34th Conference on Winter Simulation: Exploring New Frontiers, San Diego, pp. 127–135.
Riecke, B.E., Von Der Heyde, M., Bulthoff, H.H., 2005. Visual cues can be sufficient for triggering automatic, reflex-like spatial updating. ACM Trans. Comput. Logic 2 (3), 1–35.
Roussos, M., Johnson, A., Moher, T., Leigh, J., Vasilakis, C., Barnes, C., 1999. Learning and building together in an immersive virtual world. Presence: Teleoperators Virtual Environ. 8 (3), 247–263.
Roussou, M., 2004. Learning by doing and learning through play: an exploration of interactivity in virtual environments for children. Comput. Entertainment 2 (1), 1–10.
Schneiderman, B., 1983. Direct manipulation: a step beyond programming languages. IEEE Comput. 16 (8), 57–69.
Schneiderman, B., Plaisant, C., Cohen, M., Jacobs, S., 2009. Designing the User Interface: Strategies for Effective Human–Computer Interaction, Fifth ed. Addison Wesley.
Sharp, H., Rogers, Y., Preece, J., 2007. Interaction Design: Beyond Human–computer Interaction, Second ed. John Wiley and Sons Ltd..
Sherman, W.R., Craig, A.B., 2003. Understanding Virtual Reality: Interface, Application, and Design, First ed. Morgan Kaufmann Publishers.
Steed, A., 1993. A survey of virtual reality literature, department of computer science, Queen Mary and Westfield College. Tech. Rep. 623.
Sutherland, I. E., 1963. SketchPad: a man–machine graphical communication system, Proceedings of The American Federation of Information Processing Societies (AFIPS), Detroit, pp. 323–328.
Sutherland, I.E., 1965. The ultimate display. Proc. IFIP Congr. 2, 506–508.
Symanzik, J., Cook, D., Kohlmeyer, B.D., Cruz-Neira, C., 1996. Dynamic statistical graphics in the CAVE virtual reality environment, The Dynamic Statistical Graphics Workshop, Sydney, July 1996, pp. 1–11.
Usoh, M., Arthur, K., Whitton, M. C., Bastos, R., Steed, A., Slater, M., Brooks, F. P., 1999. Walking > Walking-in-Place > Flying, in Virtual Environments, Proceedings of the 26th ACM Annual Conference on Computer Graphics and Interactive Techniques, New York, NY, pp. 359–364.
Vila, J., Beccue, B., Anandikar, S., 2003. The gender factor in virtual reality navigation and wayfinding, Proceedings of the 36th Annual Hawaii International Conference on System Sciences (HICSS'03), Washington, DC, IEEE Computer Society, January 2003, pp. 101–112.
Vittorio, J. D., 1998. Navigation Interfaces for World Wide Web Browsing, Master thesis, Department of Psychology, Carleton University, Ottawa, Ontario.
Wagner, D., Pintaric, T., Ledermann, F., Schmalstieg, D., 2005. Towards massively multi-user augmented reality on handheld devices, Proceedings of the Third International Conference on Pervasive Computing, Munich, Germany, pp. 208–219.
Wang, C. Shen, H., 2005. Hierarchical navigation interface: leveraging multiple coordinated views for level-of-detail multiresolution volume rendering of large scientific data sets, Proceedings of the Ninth IEEE International Conference on Information Visualization (IV'05), London, UK, IEEE Computer Society, pp. 259–267.
Wright, T. E. Madey, G., 2008. A survey of collaborative virtual environment technologies, Technical Report, University of Notre Dame, USA.
Zaho, Z.X., 2002. Virtual reality technology: an overview. J. Southeast Univ. 32 (2), 1–10.
Zhang, S., Demiralp, C., DaSilva, M., Keefe, D., Laidlaw, D., Greenberg, B. D., Basser, P. J., Pierpaoli, C., Chiocca, E. A., Deisboeck, T. S., 2001. An immersive virtual environment for DT-MRI volume visualization applications: a case study, Proceedings of the IEEE Conference on Visualization, San Diego, CA, USA, October 2001, pp. 1406–1408.
Zhang, S., Demiralp, C., DaSilva, M., Keefe, D., Laidlaw, D., 2003. Visualizing diffusion tensor MR images using streamtubes and streamsurfaces. IEEE Trans. Visual. Comput. Graphics 9 (4), 454–462.
Zhao, Q.P., 2009. A survey on virtual reality. Sci. China Series F: Inf. Sci. 52 (3), 348–400.
Zhao, Q.P., 2011. Scientific problems in virtual reality. Commun. ACM 54 (2), 116–118.
Zheng, L., Yang, J., Cgeng, W., Huang, R., 2014. Emerging approaches for supporting easy, engaged and effective collaborative learning. J. King Saud Univ. – Comput. Inf. Sci. 26 (1), 11–160.
Zhou, N.N., Deng, Y., 2009. Virtual reality: a state-of-the-art survey. Int. J. Autom. Comput. 6 (4), 319–325.