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Head-mounted display-based intuitive virtual reality training system for the mining industry

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ABSTRACT

Virtual reality (VR) training technology in the mining industry is a new field of research and utilization. The successful application of VR training system is critical to mine safety and production. Through the statistics of the current research and applications of VR training systems in mining industry, all the input/output devices are classified. Based on the classifications of the input/output devices that are used in the VR system, the current VR training systems for the mining industry could be divided into three types: screen-based general type, projector-based customized type, and head-mounted display (HMD)-based intuitive type. By employing a VR headset, a smartphone and a leap motion device, an HMD-based intuitive type VR training system prototype for drilling in underground mines has been developed. Ten trainees tried both the HMD-based intuitive system and the screen-based general control system to compare the experiences and training effects. The results show that the HMD-based system can give a much better user experience and is easy to use. Three of the five components of a VR training system, namely, the user, the tasks, and software and database should be given more attention in future research. With more available technologies of input and output devices, VR engines, and system software, the VR training system will eventually yield much better training results, and will play a more important role in as a training tool for mine safety.

1. Introduction

Virtual reality (VR) technology is based on computer graphics, which can build virtual scenes and items to be manipulated by the user through input devices, and to be seen, heard, touched, even smelled through output devices, and the user can feel high immersion during the interaction [1–3]. By using a well-designed and built VR system, users can feel almost like they were in the real world. In VR, the environment shown is totally virtual, which is opposite to the real world, and between them there are augmented reality and augmented virtuality. All of these construct the reality-virtuality continuum [4]. Burdea and Coiffet raised the 3I of virtual reality–immersion, imagination, and interaction, as shown in Fig. 1 [2].

Entertainment, especially computer games, is one of the greatest power to promote the rapid development of virtual reality technology, and many new input/output devices designed for VR have been developed. Nowadays, there are many kinds of head-mounted display (HMD) devices in the market, such as the unibody devices–Oculus Rift, and HTC Vive or the separated devices–VR headset plus smartphone solutions. The miniaturization and portability of the VR visual devices have promoted the development of the VR industry dramatically, and there will be more affordable VR devices in the market in future.

Due to the intrinsic properties of VR–to offer almost real world experience in a harmless virtual environment–it is born to be a perfect tool for training, and is now widely used in many fields, such as military, aerospace, aircraft, surgery, etc. After decades of developments, a lot of theoretical and practical experiences have been suggested. Stone raised some basic rules and principles for developing serious games of military; Burdea and Coiffet, Stone discussed the importance of considering the factors of users; Bertram et al. have studied the effectiveness evaluation of VR training systems [2,5,6]. Though VR has been studied and utilized for several decades, there are still many aspects that need to be studied in the future, especially with the rapid technological developments in recent years.

Mining is a typical industry of high risk, and the operators in this industry require sufficient training to ensure safety. Amongst these training tasks, some are very difficult or impossible to practice in the real world, such as mine rescue, escaping from disasters, etc., which makes the VR technology very suitable as training tool

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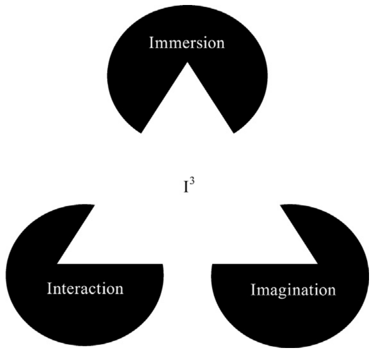


Fig. 1. 3I of virtual reality [2]

for such situations. Kizil introduces the six main benefits of using VR in mining industry, that is, reduced time, unlimited access to expensive/unavailable equipment, cost saving, ability to practice hazardous conditions, learning dispersed over a wide geographic area, and leverage existing computer investments [7,8].

In many mining countries such as Australia, the U.S., Canada, South Africa, the U.K. and China, many researchers have been studying the possibility using VR as a training tool in mining industry for the past two decades [8–15]. Dozens of prototypes have been developed, some of them have become popular products. The current popular mature VR mine training systems are mainly composed of a multi/curved screen projector, which could provide some immersion to the trainees, and customized operation platform.

In this paper, the components of VR system in mining industry are discussed. Based on the taxonomy of the input/output devices, the VR training systems for mining industry are divided into several types. A prototype of immersive and intuitive VR training system for mining industry is built and tested. Based on the test results, future research directions of VR training systems for the mining industry are proposed.

2. Input/output devices and training system classification

In essence, VR technology is the next generation media for humans to obtain artificial information, and the previous generation is based on two-dimensional screen technology. The biggest difference between them is that virtual reality technology has a completely immersive and intuitive nature of the interactive experience, which will allow users to enter a fully virtual world.

Burdea et al. introduced the five classical components of a VR system, which are VR engine, software & databases, input/output devices, user, and tasks [2]. A VR training system for the mining industry should contain the same five components (Fig. 2).

Amongst the five components of a VR mine training system, the most important one is the input/output devices, because they are the exclusive way through which users can interact with and sense the virtual environment. The current virtual reality input/output devices of VR training systems are summarized in this paper.

2.1. Input devices

Based on previous studies, the common input devices of a VR system can be classified into two categories: manually operated and automatic capturing, as shown in Table 1 [2,3,16].

One can see that these two types of input devices have great differences. Manual operation devices have a low degree of intuitive, and general devices such as keyboard and mouse are difficult to learn and use by beginners. However, manual operation devices are very mature technology, which makes them very accurate during operation. On the contrary, automatic tracking devices have a much higher degree of intuitive, and very low learning requirements, but due to the use of various sensors and new algorisms, the accuracy of the tracking operations is not guaranteed.

2.2. Output devices

A VR mine training system must have output devices so that the users could “sense” in the virtual world. According to Mazuryk et al., the visual sense and auditory sense take charge of 70% and 20% respectively of the total sensing for a human being [3,8]. The other three senses–smell, touch, and taste only take 10% (Fig. 3). Thus, visual sense is the most important one for users of a VR system.

Based on previous studies, the common visual output devices can be classified as screens, projectors, head mounted displays (HMD), and holographic devices, as shown in Table 2 [4,14].

For these technologies, the screen technology cannot provide a sense of immersion, but the price is cheap, and there are many being used in VR systems. Projector technology is very mature but costly, and CAVE is the earliest system of this type [17]. HMD has been developed a long time ago, but only with the Oculus Rift like HMD devices announced in recent years, it became more popular. Holographic projector technology is the best visual equipment solution for virtual reality, but the technology is still immature, thus cost is not well defined.

As can be seen in Table 2, there are two types of HMD, and the difference between them is mainly whether the screen is transparent or not, which will determine whether the users could see the virtual environment and the real environment at the same time. The screen of small high-res screen device is difficult to be transparent, which will block the real world eventually; while the small optical projector device is based on the optical (transparent) lens technology, hence the user can see the real world through the lens while seeing the virtual items. Strictly speaking, a small optical projector HMD device should be classified as a mixed reality device, but it can also be used in the field of virtual reality.

Through comprehensive analysis, it is found that, only HMD devices are the available devices that could provide full immersion and at a low/medium price, hence it is believed that the HMDs are the most appropriate visual devices for the VR training systems. There is an obvious problem about the HMDs–a single HMD device cannot be used by multiple users at the same time. Bednaz et al. discussed the distributed collaborative framework of VR systems for mining industry, and it turns out that this problem could be solved just by connecting several HMDs and their users into one VR system and virtual environment [18].

2.3. VR training systems for mining industry

Based on the classification of input/output devices, a new taxonomy of VR training systems for mining industry, which contains three types, is raised as follows:

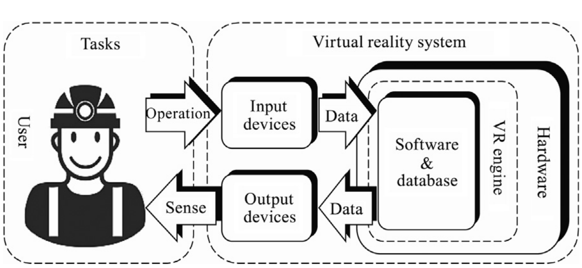


Fig. 2. Components of a VR system.

Table 1
Summary of VR input devices.

Category	Type	Device	Degree of intuitive	Degree of difficulty	Degree of accuracy
Manual operation	General	Keyboard, mouse, joysticks, etc.	Low	Medium/high	High
	Customized	Customized instruments, operational platforms, etc.	Medium	Low/medium	High
Automatic tracking	Head	Accelerometer, gyroscope, etc.	High	Low	Medium/high
	Hands	Data gloves, gyroscope, etc.	High	Low	Medium
	Eyes	Camera, IR sensor, etc.	High	Low	Medium
	Body	IR sensor, depth camera, etc.	High	Low	Medium
	Voice	Microphone, etc.	High	Low	Low/medium
	Position	Magnetic/optical/mechanics sensors, etc.	High	Low	Medium/high

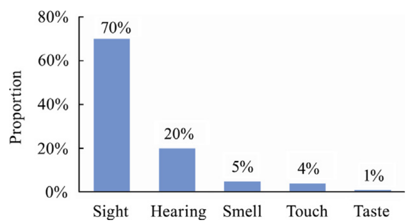


Fig. 3. Contributions of the five human senses.

(1) Screen-based general VR training system

The screen-based general system uses general physical devices, such as keyboard and joystick as input devices, and desktop monitor as output device [19,20]. The whole system has little/none immersion, and is mainly used to develop the basic VR mine training systems.

(2) Projector-based customized VR training system

The projector-based customized VR training system is currently the most popular VR training system for mining industry. The output devices for visual sense are projectors with different kinds of screen fabrics–flat, multiple, curved, or domed, etc. At the same time, many customized operational platforms based on the real equipment are widely used in this kind of system. With the help of projectors and large screen fabrics, this system could provide some immersion to the users. There are quite some commercial products in the market based on this kind of VR training system, such as CAE mining and QinetiQ products.

(3) HMD-based intuitive VR training system

The HMD-based intuitive system means that the high immersive visual output devices (head mounted display) and intuitive input devices (automatic tracking devices) are employed in the system. In this VR system, trainees can feel full immersion, and interact with the virtual environment and equipment naturally and intuitively. For now, the immersive natural system is not widely developed and used, but it is believed to be the most advanced system and the future of mine VR training systems [21].

3. HMD-based intuitive VR mine training system

3.1. System components

In this study, a new HMD-based intuitive VR training system is built for drilling scenario training in underground mines. The components of this VR training system are as follows: (1) user: new drill worker in an underground mine; (2) Input/output devices; (2.1) input devices; (2.1.1) automatic head tracking devices–sensors in the HMD; (2.1.2) automatic hand tracking device–leap motion; (2.2) output devices: HMD; (3) VR engine: unity 3D personal edition; (4) software and database: generated by unity 3D after setting the training procedures; and (5) tasks: borehole drilling based on operating procedures.

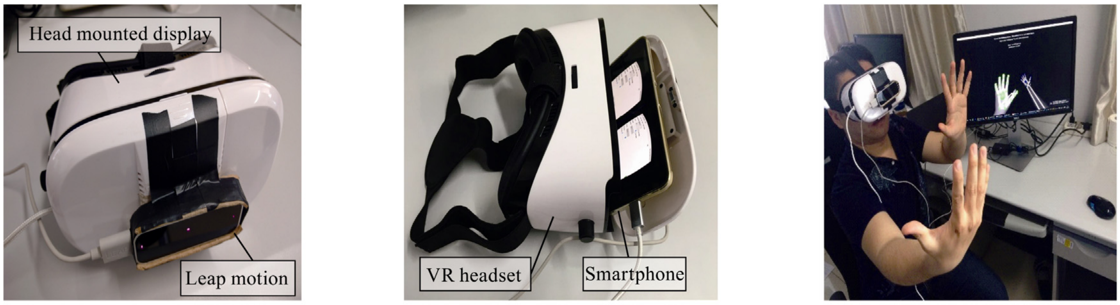
In this VR training system, it is the input/output devices that make this system unique from other VR training systems. Fig. 4 shows the input and output devices used in the system. Fig. 4a shows the HMD used by the system, including a shell and a smart phone. Fig. 4b shows the system input device leap motion and output device HMD, in which leap motion is connected in front of the HMD. Fig. 4c shows the user operating the system input/output devices: users could see the virtual scene through HMD. Meanwhile the hand movement and gestures of the user can be recognized and displayed in a virtual scene, and the user can interact with the virtual scene just by hand movements.

The automatic capture function of the input devices of this system mainly includes two parts: the head motion capturing and the hands tracking. The head tracking is needed in order to realize the real-time updating of the virtual reality display, and hand tracking is needed to realize the intuitive operation. With the help of the sensors built in the smartphone, such as the gyroscope and the accelerometer, the smartphone could track the user's head turning. Meanwhile, the leap motion equipment can detect the distance between user's hands and the infrared camera, which will then calculate the location of the hands. Through the phone sensor and leap motion, the system can track the head and hands in real-time.

The output device of this system is the head-mounted display–HMD. The HMD used in this system is a split-type device, which consists of a Nexus 6P smartphone and a VR headset. The smartphone is connected to the computer through the USB cable, and with the help of Trinus software, the normal computer screen

Table 2
Summary of VR display devices.

Category	Type	Immersion	Number of user	Cost
Screen	Normal screen	None	Single	Low
	3D screen	None	Single	Low
Projector	Flat screen fabric	Partial	Single/multiple	Medium
	Curved/multi-screen fabric	Partial	Single/multiple	High
HMD	Small high-res screen	Full	Single	Low/medium
	Small optical projector	Full	Single	Medium
Holograms	Holographic emitter	Full	Single/multiple	N/A



(a) Composition of the HMD (b) Input device and Output device (c) Recognition of user's hands

Fig. 4. HMD and leap motion as I/O devices.

can be converted to the VR format and displayed on the phone screen. Combined with the head automatic capture device, as well as various sensors in the smartphone, the HMD can update the screen in real-time according to the rotation of the user's head, hence the user can obtain a full immersion experience.

3.2. Drill training programming

As to software & database and VR engine part, the Blender and Unity 3D software were employed: the virtual miner model was built in Blender, and the underground coal mine scene, the trigger and interaction rules between the user and the virtual environment, etc., were developed and coded in Unity 3D.

In Fig 5, the left-side pictures show the real utilization situation of each system, and the right-side pictures show that the graphics that the user can see from the screen or the HMD. In the screen-based general system (Fig. 5a), the user is controlling the object to drill by using a joystick, and the screen shows a person in the drilling scenario, which means that the immersion of the system could not be high. Whereas in the HMD-based intuitive system (Fig. 5b), the user can experience the first person view through the HMD, and at the same time, thanks to the gyroscope built in the smartphone, the turning of the head could be monitored, and the sight in the HMD could change in real time. What's more, the user can manipulate the virtual miner's hands directly, instead of the whole virtual character, and through the leap motion device, the user can control the fingers respectively, which means the user can perform more complicated movements and gestures to interact with the virtual drill in the virtual environment.

3.3. Results

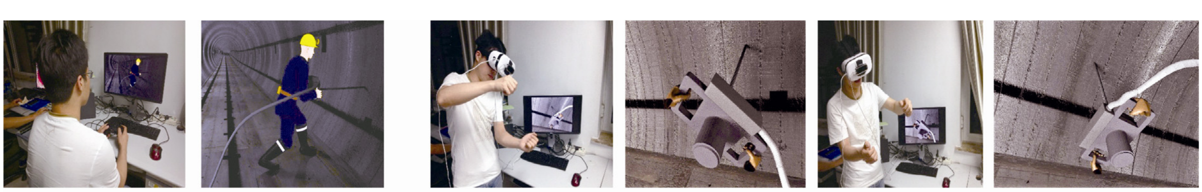
To evaluate the effects of each mining training system, ten student trainees tried both the HMD-based intuitive and screen-based general training systems. They then filled out questionnaires about the two systems to evaluate the levels of immersive, intuitive, interactive, ease of use, and ease of learning. Each aspect was evaluated on a scale from 0 to 5. The results are shown in Fig. 6.

It is found that the HMD-based intuitive VR training system has a dramatically higher score of immersion (4.8 out of 5) than the screen-based general system out of 5, and 1.5 to 2 times higher grade of intuitive, interactive and ease of use. This means that the HMD-based system has a better user experience. As for the ease of learning, the training results of each system, the screen-based system is only a little lower than the HMD-based system, which means that both systems have good training results; the HMD is only slightly better. After experiencing both systems, 9 of 10 students prefer the training experience with the HMD system, and prefer to use it in future.

The student trainees also suggest some limitations of the current HMD-based intuitive VR training system, which are as follows:

(1) In the HMD system, a user could not move the character by moving his own arms. Instead he must use other devices such as keyboard or joystick. This will lower the immersion of the system. The Microsoft Hololens offers a great idea to solve the problem. It is a standalone device which contains all required hardware and software to operate;
(2) With long-time utilization of HMD, the user gets tired or feels motion-sick. Huang et al. even created a new HMD with light field displays to help the users avoid the motion sickness [22];
(3) For the current system, the leap motion device is used to track the user's hands, while the user could not feel any tactile sense, which will also reduce the immersion of the system, because when users see they are touching something in the virtual environment, they could not feel the tactile sense in the real world;
(4) Users can only interact with the drill, but could not interact with other things in the virtual environment, which is due to the limitation of the current software & databases.

The above-mentioned are the main limitations of the current HMD-based VR system, and most of them are due to the limitations of the hardware and software used in the system. With the development of the VR input/output devices, and the update of



(a) Screen-based general VR training system (b) HMD-based intuitive VR training system

Fig. 5. Two different training systems.

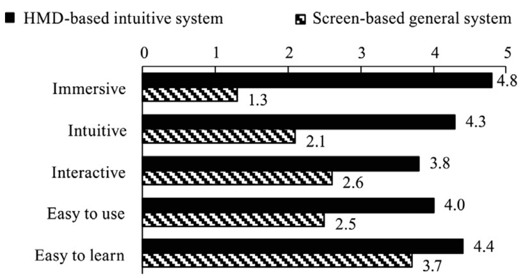


Fig. 6. Evaluation of training systems.

the HMD-based VR training system, all the limitations of the current system can eventually be solved in future.

4. Discussion

4.1. Factors affecting the training results

Essentially, VR technology is a new way of content displaying and human-machine interaction. Many researchers, including this study, have suggested that the VR training systems are proven effective, and with higher immersion, users can get better training results [6,13,21,23,24]. However, immersion is only one of the 3I of virtual reality (Fig. 1), and the degree of immersion is mainly determined by the input/output devices.

In recent years, the main technological breakthroughs of VR are in the visual output devices, such as Oculus Rift, HTC VIVE, Sony Playstation VR, etc. There are other input devices developed as well, such as the Virtuix Omni treadmill. The newly invented input/output devices have dramatically increased the degree of VR immersion, and it is believed that the more immersive the VR training system is, the better the user experience will be.

Although there are still a lot of improvements of the input/output devices to be made, such as the auditory and tactile experience, they can only improve the immersion of the virtual reality training system. The other four components also affect the VR training results.

Nowadays, the most critical drawback of the current VR technology is the lack of high quality content, that is, the creation of virtual reality content cannot keep up with the developments of hardware. In mining VR training systems, the "content" means the virtual environment, virtual characters, training scenarios, and training tasks. In addition to the I/O devices, all other four components of VR training system will affect the quality of the system "content".

(1) VR engine: the VR engine is the fundamental software, and it determines the human-computer interaction results. For instance, if a trainee is drilling into the wall, there should be drilling fragments coming out of the borehole and falling on the floor. In other words, the VR engine will determine the degree of authenticity of the VR training system.
(2) User: different users have different characteristics, and they should be considered seriously [5,25,26].
(3) Tasks: these indicate the purpose of the VR training.
(4) Software and database: this is based on the VR engine, and takes charge of computing the input data (manipulating signals) and output data (video, sound, etc. signals), and saving and loading of the data of the virtual reality training system. To create more real underground mine models, Zlot et al. studied the 3D reconstructing method [27].

4.2. Future research

To enhance the VR training system for the mining industry, all five components of a VR system are worth studying. Amongst the five components, the author believes that the development of the input/output devices and VR engine can greatly influence the promotion of the application of VR technology in the mining industry. It is the specialized hardware manufacturers and software companies, however, who should develop more intuitive input devices, more immersive output devices, and more powerful VR engines. The other components of mine virtual reality training system–users, software & database, and tasks–are topics for future research for the mining industry practitioners.

Users are the most important factor that should be given more attention to a VR mine training systems. Users in mines are mainly mining industry practitioners, who have distinct characteristics: the cultural level of the clear majority is not high, the ability to accept new things is weak, and they do not want to spend too much time learning. It is vital to build the VR mine training system to suit this kind of users.

Tasks are equally an important factor, and all kinds of training tasks are the main purpose of the VR training system. All software development and database setting should focus on the training tasks.

As for the software and database, they are the only measures for the users to finish the training tasks. In the development of software, it is necessary to consider these characteristics and offer users a special treatment to meet the required ease of use. In the Cardboard Design Lab app, Google discusses how to make a better VR scene, and mine VR content production also has some guiding role.

In conclusion, future research emphasis of the VR training system for the mining industry, is to study three components of the system: user, tasks, and software & database. Meanwhile, the state of the art input/output devices and VR engine in the market should also be exploited. In other words, all five components of VR training system should be improved simultaneously.

5. Conclusions

(1) This paper classifies the input/output devices of mine VR training system, and classifies the systems into screen-based general system, projector-based customized system, and HMD-based intuitive system, based on the difference of I/O devices.
(2) Using the head mounted display as output device, and the leap motion as input device, an HMD-based intuitive VR training system was built. Users can feel full immersion through the HMD and control the virtual character's hands to manipulate the drill simply by moving their own hands.
(3) After 10 student trainees tried both the HMD-based intuitive system and a controlled screen-based general system, they found that the HMD-based system is more immersive, intuitive, interactive, and easy to use.
(4) The most critical drawback of the current virtual reality training system is the lack of high quality content. Although all five components of the VR system will affect the content quality, the three components of user, tasks, and software & database should be given more attention.

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