

Design of a Simulated Michelson Interferometer for Education Based on Virtual Reality

Hongling Sun, Xiaodong Wei, and Yue Liu^(✉)

Beijing Engineering Research Center of Mixed Reality and Advanced Display,
School of Optoelectronics, Beijing Institute of Technology,
Beijing 100081, China
liyue@bit.edu.cn

Abstract. The physical experiment based on science inquiry learning shows its advantages compared with traditional class demonstration. However, the participation in physical experiments is often stylized and there are still many limitations when promoting the laboratory learning. This paper presents the construction of a Virtual Optics Laboratory which is applied to the experiment of the Michelson interferometer. On the current platform, the phenomena of interference and background theories are visualized for the purpose of efficiently promoting conceptual understanding. Factors of the experimental environment such as wavelengths, properties of optical elements and perspectives can be altered with interactive tools, enabling students to set up the system, observe the phenomena of interference as well as measure wavelengths and small displacements. The simulated laboratories can be of great assistance in the development of inquiry skills to enhance school education.

Keywords: Simulated Michelson interferometer · Visualization · Interaction · Virtual reality

1 Introduction

Research shows advantages for science inquiry learning where students conduct investigations compared with typical instruction featuring lectures or teacher demonstrations and the value of physical laboratories for science learning is generally recognized [1]. However, there are many limitations and problems when promoting the laboratory learning. Firstly, schools located in remote areas may not be equipped with advanced facilities which are essential to physical hands-on experiments. Secondly, even for students who can get access to the facilities, the participation in laboratory experiments is often stylized in which the students just follow the instructions to manipulate devices, collect data and draft experimental reports which function as the main reference for teachers' evaluation. What's more, since students usually work in groups in the physical laboratory, those diligent and capable members may undertake most work while others just take a free ride.

As for the optics laboratory as shown in Fig. 1(a), students often possess some misconceptions about the electromagnetic wave, interference, diffraction and polarization etc. when taking part in the experiments although the comprehension of such qualitative concepts is a basic prerequisite for many higher-order concepts [2]. When performing the experiments, it is hard for students to feel confident since they are unfamiliar with optical elements along with the experimental environment. Students tend to neglect the experimental principles as they just follow the operation steps described on the textbook. In addition, optical elements are easy to be soiled or broken and the alignment of rays calls for extremely high accuracy. To save cost as well as time, teachers tend to set up the equipment, calibrate the devices in advance and just let students complete the following work in real optics laboratories.

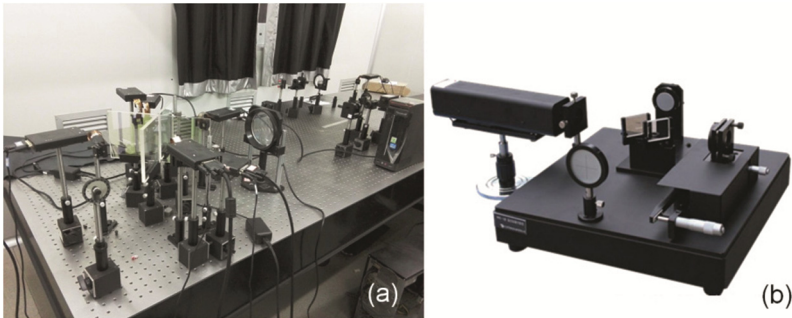


Fig. 1. (a) The optics laboratory in reality (b) the Michelson interferometer

The virtual reality technology [2] can help to address the mentioned problems with the visualization of the laboratory environment and the simulation of experimental procedures with a relatively low requirement for equipment. Participants are immersed in the virtual laboratory and the interaction methods for altering the relative factors are flexible to arouse interests as well as develop their inquiry skills. This paper presents the construction of a Virtual Optics Laboratory and the system of the Michelson interferometer experiment which allows students to set up and calibrate the apparatus, observe the phenomena of interference, measure wavelengths and small displacements in the immersive environment. Section 2 presents the virtual reality technology and its applications in education. The construction of the Virtual Optics Laboratory and the simulated experiment of the Michelson interferometer are described in Sect. 3 and follow by the conclusion in Sect. 4.

2 Virtual Reality Technology and its Applications in Education

Virtual reality is an emerging technology that was first proposed in 1960s [2] and can be defined as a synthetic environment which gives its user a feeling of “being there” [3]. It develops rapidly with the continuing improvements of high-performance graphical processing unit and the display technology, allowing the creation of increasingly convincing virtual environments [4]. So far there have been extensive applications of

virtual reality in the areas such as remote operation [5], task assistance [6], manufacturing planning [7], preservation of culture [8] and the enabling technology has reached a sufficient level of maturity for it to be seriously applied to education [9], training [10], and research in higher education [11].

Virtual reality augments learning with experience [10], offering an unprecedented avenue for the delivery of experiential education to students of all ages and in all disciplines [2]. It is certain that the flexibility provided by a system of virtual reality will be a major attraction to the educational community [11] and the high level of interactivity and immersion makes the learner an active participant. Researches show that the experience of immersion can enhance education in at least three ways: by allowing multiple perspectives, situated learning, and transfer [12]. The world of virtual reality can also be used to circumvent the physical, safety, and cost constraints that limit schools in the types of environments they can provide for learning-by-doing [11]. Besides, virtual laboratories add value to physical experiments by allowing students to explore unobservable phenomena [1]. For example, it would be very helpful to allow students to study the transmission of invisible light such as infrared or ultraviolet rays which could be visualized by adding some special effects in the virtual environment.

3 The Virtual Optics Laboratory and the Michelson Interferometer Experiment

A Virtual Optics Laboratory was constructed, offering an immersive environment for the conduction of various optical experiments. The configuration of the Michelson interferometer which was invented by Albert Michelson aiming at measuring the relative speed between the earth and the ether is shown in Fig. 1(b). The Michelson-Morley experiment denied the ether hypothesis and proved the constancy of the light speed, which is of great meaning in the history of physics. Since the Michelson interferometer is the basis of many other interferometers and learning about its principles assists students to develop a better understanding of the wave theory as well as the interference theory, the Michelson interferometer experiment, as one of the most classical optical experiments, is designed and conducted in the Virtual Optics Laboratory.

3.1 Software and Hardware Environments

Because computer technologies now offer virtual laboratories where investigations involve simulated material and apparatus [1], it is a feasible idea to promote virtual laboratories in the schools that are not so well-equipped, with all the resources being shared on the Internet. The models of optical elements as well as the laboratory furniture can be downloaded from 3D warehouse and modified with SketchUp. The optical elements used in the experiment include a laser, two mirrors, a collimating lens, a beam splitter, a compensating plate, a reference mirror, a measuring mirror, an imaging lens and a screen.

The virtual scene for the experimental platform is rendered in Unity. With a powerful engine and integrated development environments, Unity helps to realize the real-time performance of 3D scenes. Interfaces used in the experiments are drawn with NGUI, a plug-in compiled with C# that provides event notification frameworks and many animation effects.

Compared with laboratory experiments, it is more convenient for students to perform virtual experiments because only a personal computer is required to operate this Virtual Optics Laboratory with the mouse and the keyboard to input instructions. The experimental system also offers alternative display techniques so users can choose to view the experimental scenes on the desktop screens or utilize head mounted displays (HMDs) to achieve better sensory immersion, as shown in Fig. 2(a) and (b).

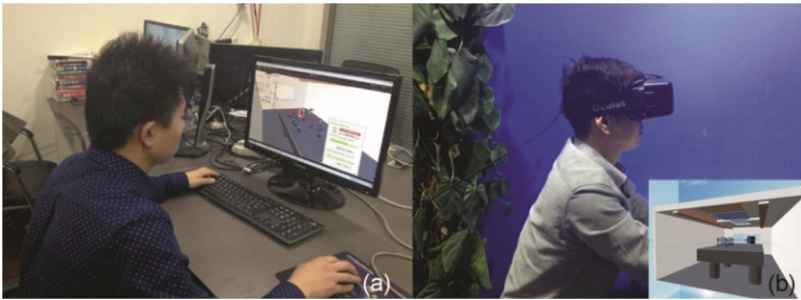


Fig. 2. (a) Viewing the virtual laboratory on the desktop screen (b) viewing the virtual laboratory through the HMD

3.2 Visualization

Teaching Videos. In general, it is not enough for students to gain a thorough comprehension of quite abstract optical conceptions in class but they have to enter the real laboratories with these misconceptions, which is obviously not beneficial to accelerate their learning process. So the experimental system of the Michelson interferometer that is presented here in the Virtual Optics Laboratory covers the teaching content of basic knowledge which is demonstrated by videos so that some conceptions and theories such as the wave theory of light can be visualized and interpreted by animations, making a vivid impression on students and helping with their comprehension. Besides, some background information which is useful to arouse the learner's interest on optics may not be mentioned in real classes, e.g. the history of the Michelson interferometer and its relationship with the ether hypothesis. The teaching videos can involve all the meaningful information.

The teaching process will take a period of time and participants tend to feel impatient watching the complex demonstrations without a break. So the videos are divided into four parts which cover “the nature of light”, “the ether hypothesis and Michelson-Morley experiment”, “the interference theory” and “the principle of the Michelson interferometer” as shown in Fig. 3, to help the participants to concentrate better and learn efficiently.

For the purpose of improving the level of interaction, there are interaction pages after each video which contains either questions or small games. Only when students answer the question correctly or succeed in the game can they have access to the next part, otherwise they have to watch the video again.

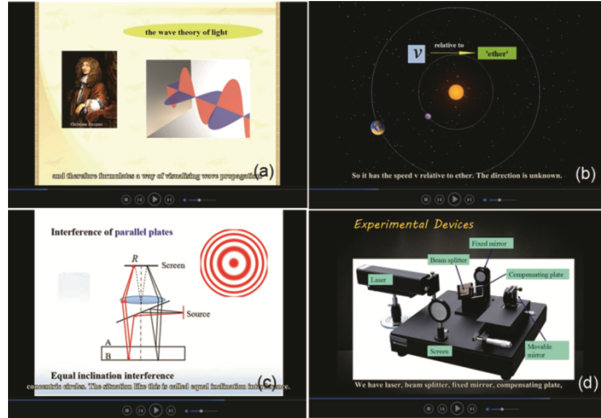


Fig. 3. Teaching videos (a) the nature of light (b) ether hypothesis and Michelson-Morley experiment (c) interference theory (d) the principles of the Michelson interferometer

Interference Fringes. One of the limitations of traditional optical experiments is that they are not so helpful when it comes to the investigation of unobservable or unobvious phenomena. The Virtual Optics Laboratory can fix this problem by visualizing the light rays and the interference fringes without environmental disturbances. Virtual rays can demonstrate the traveling path of light but they cannot interfere with each other and generate interference patterns. The system is for educational use so it is significant to display the interference patterns according to the theoretical calculations. Since it is extremely convenient to conduct matrix calculations with MATLAB, the interference patterns drawn with MATLAB are imported into Unity and displayed on the virtual screen.

According to the interference theory, if two light waves interfere with each other, the resultant light intensity I is described as follows, where I_1 and I_2 are respectively the intensity of two initial light waves while $\Delta\varphi$ is the phase difference.

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\Delta\varphi) \tag{1}$$

With MATLAB, the intensity of each point in the picture is derived from several parameters in the experimental setup. For the equal inclination interference, the interference pattern is drawn in the size of $721 \times 721 \times 3$ pixels. To get the intensity value of each pixel in the picture, some transforms need to be conducted from the size of screen in millimeters to the size of picture in pixels. The intensity value of each pixel is shown in Eqs. (2) and (3), where $r(i, j)$ is the theoretical distance between the point (i, j) and the center of the picture while $screen\ size$ is the size of the screen. f is the focal length of the

imaging lens and d is the relative position between the measuring mirror and the reference mirror. The sample equal inclination interference patterns are shown in Fig. 4(a).

$$r(i, j) = \frac{\sqrt{(i - 361)^2 + (j - 361)^2}}{360} \cdot \frac{screensize}{2} \quad (2)$$

$$I(i, j, 1) = 1 + \cos\left(\frac{2\pi}{\lambda} \cdot 2d \frac{f}{\sqrt{f^2 + r^2}}\right) \quad (3)$$

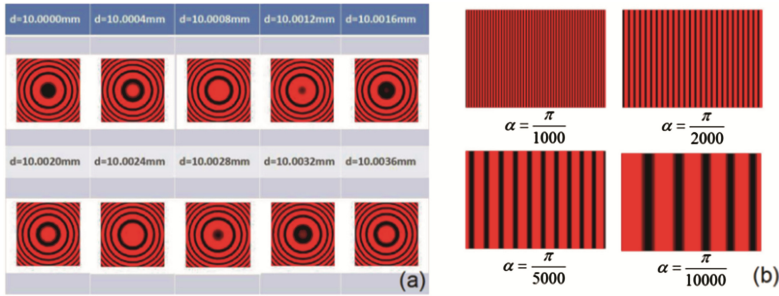


Fig. 4. (a) Equal inclination interference patterns (b) equal thickness interference patterns ($\lambda = 632.8 \text{ nm}$, $f = 100 \text{ mm}$, $screensize = 3 \text{ mm}$)

For the equal thickness interference, the interference pattern is drawn in the size of $721 \times 500 \times 3$ pixels. The calculation of the intensity value of each pixel is shown as follows, where α is the angle of the measuring mirror. The sample equal thickness interference patterns are shown in Fig. 4(b).

$$d(i, j) = 1 + (j - 361) \times \tan(\alpha) \quad (4)$$

$$I(i, j, 1) = 1 - \cos\left(\frac{2\pi}{\lambda} \cdot 2d \sqrt{1 - \frac{r^2}{f^2 + r^2}}\right) \quad (5)$$

3.3 Interactions

Perspectives of Users. After entering the Virtual Optics Laboratory, it is significant for users to observe the experimental platform from different perspectives in order to get acquainted with the experimental environment. As the immersion degree increases, the controls and feedback need to be appropriately correlated in a step-by-step manner so that users can successfully manage the main controls and feel confident to continue [8]. The instructions are given to teach users to zoom in or out as well as to rotate the viewing angle with the mouse. In this way, users can get familiar with the controls and concentrate on the experimental environment.

Position Adjustments of the Optical Elements. Optical elements such as the measuring mirror need to be adjusted with high accuracy in the experiment. In the real experiment, the micrometer screw is used to control the movement of the measuring mirror but it is of great complexity for an inexperienced student to use. In the virtual experiments, a slider is set on the control panel for the fine adjustment of the measuring mirror as shown in Fig. 5(a). The control panel is a sprite placed on the corner of the screen and integrated with the commands necessary for the experiments. The shift of the sliding box is correlated with the translation of the measuring mirror and the value of the mirror’s displacement will be displayed in a textbox.

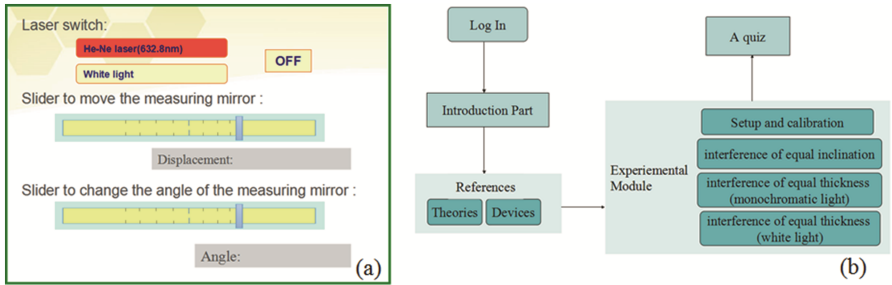


Fig. 5. (a) The control panel (b) the flowchart of the virtual Michelson Interferometer experiment system

Angle Adjustments of the Optical Elements. For the observation of equal thickness interference, the angular adjustment of the measuring mirror also requires high accuracy. One solution is that a textbox for inputting the value of angle can be created on the control panel. But in this way, the angle won’t change continuously and neither will the interference pattern. In addition, only when the angle of the measuring mirror changes within the specific range could the interference fringes be observed on the screen. But the students are not aware of the range and don’t know how to input the proper value. Another approach is similar to the fine adjustment of the position. A slider is used to control the angle whose value will be displayed in a textbox. The range of the slider is mainly occupied by the angular range in which the interference fringes of equal thickness are obvious enough to be seen.

The experiment also needs the switch for the laser which is also set on the control panel. Users can click on the button to turn on/off the laser as well as to decide whether the light is monochromatic or polychromatic.

3.4 The Flowchart and Interfaces

The flowchart of the experimental system is described in Fig. 5(b). In the Virtual Optics Laboratory, students no longer work in groups and everyone has to complete the experiments on their own. The system is quite customized and can log each student’s performance, which allows the students to review their manipulation and helps the teacher to identify the ones who need specialized tutoring [1]. As shown in Fig. 6(a), the login

interface is arranged at the entrance of the Virtual Optics Laboratory system. Students may be unfamiliar with the experimental environment and procedures at the very beginning so the introduction page along with the teaching videos covering basic knowledge necessary for the following experiments comes after the login interface, as shown in Fig. 6(b).

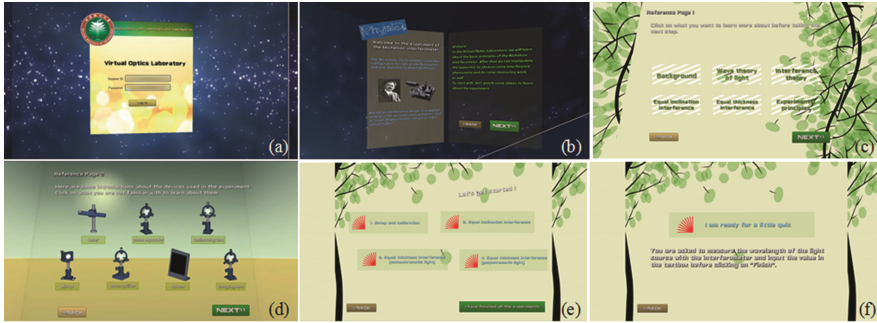


Fig. 6. Interfaces (a) log in (b) introduction part (c) reference to experimental principles (d) introductions to devices (e) experimental module (f) quiz

Since not everyone can remember all the information mentioned in the teaching videos, two reference pages are arranged in the experimental system in case they need to look up some detailed information about the experimental principles and devices, as shown in Fig. 6(c) and (d). If a student wants more detailed information about the interference theory, he/she can click on the corresponding button and then a sprite will appear explaining relevant knowledge in the forms of words, formulas and diagrams.

As shown in Fig. 6(e), four experimental parts are linked to four buttons on the experimental module page, including “setup and calibration”, “interference of equal inclination”, “interference of equal thickness (monochromatic light)” and “interference of equal thickness (polychromatic light)”. In order to evaluate the learning outcomes of the participants, there is a small quiz at the end of the system as shown in Fig. 6(f).

3.5 Experimental Procedures

Setup and Calibration. In reality, students seldom have chances to set up and calibrate apparatus in optics experiments due to the complexity of optical systems but the Virtual Optics Laboratory system can make up for it by allowing students to manipulate models of devices on the virtual experimental platform without worrying about smudging or breaking any optical elements. During the experiment, students need some instructions to guide their manipulation so a small sprite is set beside the 3D experimental scene as a guidebook to be referred to in each step. The experimental schematic (Fig. 7) and instructions are shown on the sprite. Following the instructions, students place devices on the corresponding positions, turn on the laser and observe how the light transmits.

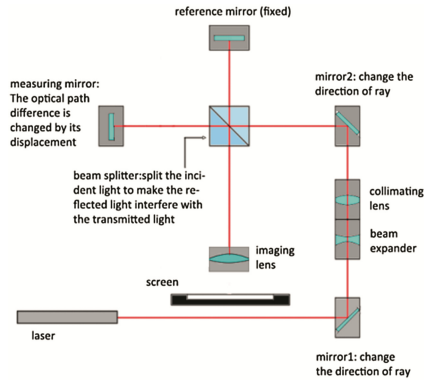


Fig. 7. Experimental schematic

In the Virtual Optics Laboratory, the calibration work is simplified and students only need to guarantee that the light goes through or gets reflected on the center of devices. For a device in the light path, if the position is still biased, the emergent ray will be set darker compared with the incident ray. Once the devices are calibrated well one by one, all the sections of light rays will share the same brightness and interference patterns would appear on the screen.

Interference of Equal Inclination. Students are encouraged to measure small displacements of the movable mirror in the experiment of equal inclination interference. If the relative position between the reference mirror and the measuring mirror changes, the difference between the two split optical paths will change and so will the interference pattern.

Students are instructed by the guidebook to move the measuring mirror slowly along the light path, observing the screen and counting the number of the fringes that have poured out or in, as shown in Fig. 8. After that they are required to input the number and calculate to get the value of the displacement.

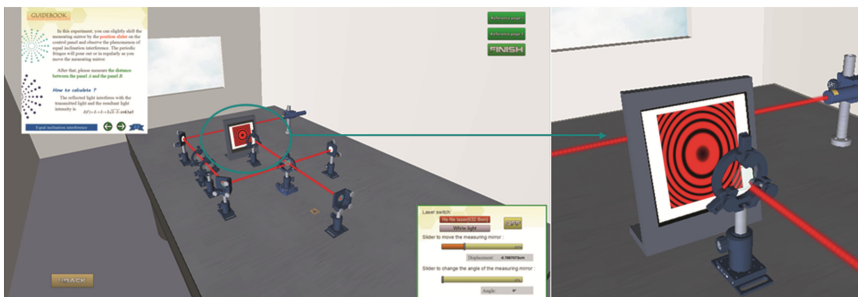


Fig. 8. The experiment of the equal inclination interference

Interference of Equal Thickness. This experiment consists of two parts, equal thickness interference of the monochromatic light and the polychromatic light, as shown in Fig. 9. In the part of the monochromatic light, students turn on the laser and change the angle of the measuring mirror slightly with the control panel. Straight stripes would appear on the screen, evenly spaced. The stripes will change in pace with the change of the measuring mirror's angle. In the part of the polychromatic light, the student can switch the light source to "white light". Then he/she is instructed to change the angle of the measuring mirror slightly and observe how the colored fringes form on the screen.

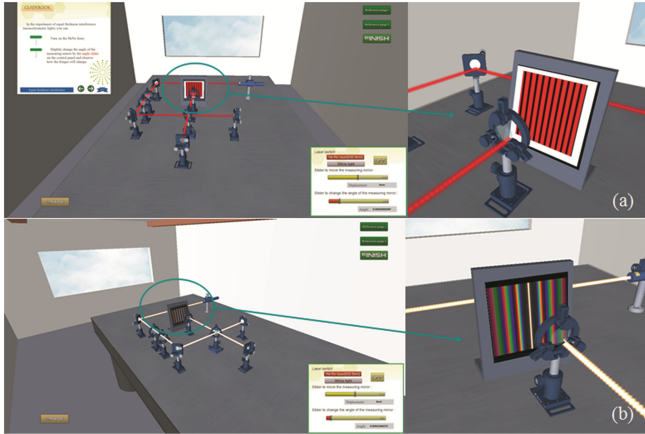


Fig. 9. The experiment of the equal thickness interference (a) equal thickness interference of the monochromatic light (b) equal thickness interference of the polychromatic light (Color figure online)

4 Conclusion and Future Work

Experimental experiences are significant for students to investigate scientific phenomena and develop inquiry skills. Virtual reality technologies could contribute to the learning process in school education by enabling each student to get access to the virtual customized experiments, making up for the lack of equipment in some areas. The immersive learning experiences inspire the participants to explore the unfamiliar events and solve problems independently. The Virtual Optics Laboratory presented in this paper adds value to traditional optics experiments by the high efficiency as well as the visualization of some unobservable phenomena and confusing conceptions, enabling students to get a better understanding of basic knowledge and enhance their experimental skills.

However, it is clear that the virtual experiments cannot replace the physical hands-on experiments totally although both of them can achieve similar goals. After all, the scientific research should be based on authentic materials and students ought to experience challenges in reality and learn to take all the factors into consideration to solve problems. Combinations of physical and virtual experiments can capitalize on the

features of each approach [1]. So the Virtual Optics Laboratory system can function as a tool which assists students to preview or review the realistic hands-on experimentation.

For the virtual laboratory system, further work is needed to improve the level of interaction and immersion. Traditional input methods like the mouse and the keyboard can be replaced by gesture recognition technologies. Besides, the augmented reality technology could also be applied to the virtual experiments. For example, different markers can be utilized and when users shift the markers on the table, the camera will capture the markers and overlay the corresponding virtual devices on them in the screen. In this way, students would feel that they are moving the real devices on the table. It is also important to extend the applications of the Virtual Optics Laboratory to other optical experiments and the system can be also made web-based to support the remote teaching.

Acknowledgments. This work has been supported by the National Natural Science Foundation of China (Grant No. 61370134) and the National High Technology Research and Development Program (Grant No. 2013AA013904).

References

1. De Jong, T., Linn, M.C., Zacharia, Z.C.: Physical and virtual laboratories in science and engineering education. *Science* **340**(6130), 305–308 (2013)
2. Bowen Loftin, R., Engleberg, M., Benedetti, R.: Applying virtual reality in education: a prototypical virtual physics laboratory. In: *Proceedings of IEEE 1993 Symposium on Research Frontiers in Virtual Reality, 1993*, pp. 67–74. IEEE (1993)
3. Jayaram, S., Connacher, H.I., Lyons, K.W.: Virtual assembly using virtual reality techniques. *Comput. Aided Des.* **29**(8), 575–584 (1997)
4. van Veen, H.A.H.C., Distler, H.K., Braun, S.J., et al.: Navigating through a virtual city: using virtual reality technology to study human action and perception. *Future Gener. Comput. Syst.* **14**(3), 231–242 (1998)
5. Ding, G., Zhang, J., He, Y., et al.: VR-based simulation on material handling remote operation for engineering machine. In: *Fourth International Conference on Image and Graphics, 2007, ICIG 2007*, pp. 984–989. IEEE (2007)
6. Oda, O., Sukan, M., Feiner, S., et al.: Poster: 3D referencing for remote task assistance in augmented reality. In: *IEEE Symposium on 2013 3D User Interfaces (3DUI), 2013*, pp. 179–180. IEEE (2013)
7. Doil, F., Schreiber, W., Alt, T., et al.: Augmented reality for manufacturing planning. In: *Proceedings of the Workshop on Virtual Environments 2003*, pp. 71–76. ACM (2003)
8. Chen, S., Pan, Z., Zhang, M., et al.: A case study of user immersion-based systematic design for serious heritage games. *Multimedia Tools Appl.* **62**(3), 633–658 (2013)
9. Valdez, M.T., Ferreira, C.M., Maciel Barbosa, F.P.: Distance education using a desktop virtual reality (VR) system. In: *Proceedings of the 24th EAEEIE Annual Conference (EAEEIE), 2013*, pp. 145–150. IEEE (2013)
10. Psotka, J.: Immersive training systems: virtual reality and education and training. *Instr. Sci.* **23**(5–6), 405–431 (1995)
11. Kim, J.H., Park, S., Lee, H., et al.: Virtual reality simulations in physics education. *Interact. Multimedia Electron. J. Comput. Enhanced Learn.* **3**(2) 2001
12. Dede, C.: Immersive interfaces for engagement and learning. *Science* **323**(5910), 66–69 (2009)